FRONTISPIECE

Kootenay Lake: view to the south from near Woodbury Point. To the east of the lake are the Purcell Mountains, to the west, the Selkirks. The low, conifer-clad promontory to the southeast, is the Crawford Bay Peninsula. In the right foreground is the stream delta of Woodbury Creek.

UNIVERSITY OF ALBERTA

A STUDY OF GARNETS AND HOST ROCKS FROM THE CENTRAL KOOTENAY LAKE AREA, SOUTHEASTERN BRITISH COLUMBIA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A Study of Garnets and Host Rocks from the Central Kootenay Lake Area, Southeastern British Columbia", submitted by Christopher J. Dodds, B.Sc., in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Garnetiferous amphibolites are abundant throughout the Cambro-Ordovician Lardeau Series on the eastern side of Kootenay Lake, but are absent in the younger, Carboniferous-Triassic Milford and Slocan Series. Garnet-bearing schists are most plentiful in the Cambrian Plaid Lake Formation, and in formations younger than the Ordovician. The syntectonic Kootenay Intrusives are notably peraluminous, and carry garnet.

The amphibolites examined, both garnetiferous and non-garnetiferous, are remarkably similar in chemical composition. They compare well with the C.I.P.W. norm of normal tholeiitic basalts and dolerites, and could conceivably be related to the Kaslo Volcanics. The schists examined are more variable in composition, and are best regarded as metamorphosed semipelites.

New data are presented for twenty-five garnets: fifteen from amphibolites, eight from schists, and two from acid igneous material. The average molecular composition of garnets from amphibolites is found to be $Alm_{52.3}Sp_{4.5}Pyr_{11.9}Gro_{23.3}And_{8.0}$, while those from schists and acid igneous material average $Alm_{74.8}Sp_{3.5}Pyr_{11.0}Gro_{1.4}And_{9.3}$, and $Alm_{66.8}Sp_{25.0}Pyr_{2.5}Gro_{0.9}And_{4.8}$, respectively. All the garnets from the central Kootenay Lake amphibolites plot outside the "solubility field" limits for pyralspites proposed by Winchell (1951).

A linear relationship between the physical parameter ratio a_o/N and the CaO content is demonstrated for the Kootenay Lake garnets irrespective of their host rock type. No systematic trends in garnet composition related to metamorphic grade are found for garnets either from schists or amphibolites. The CaO and MnO

content of garnets from schists, and the MnO content of garnets from amphibolites, vary despite almost uniform whole rock CaO and MnO content. However, the CaO content of garnets from amphibolites varies sympathetically with whole rock CaO content.

The coexistence of garnetiferous and non-garnetiferous amphibolites within the central Kootenay Lake area is considered to be neither a function of T nor P differences, nor of substantial chemical compositional differences. The development of felsic-rich selvages or rims about garnets from amphibolites is interpreted as the result of retrograde metamorphic change.

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CHAPTER I

INTRODUCTION

NATURE OF THE STUDY

This investigation concerns a petrographical, mineralogical, and chemical study of garnets and their host rocks from the central Kootenay Lake area, in southeastern British Columbia. A selection of thirty-eight rocks was made for the purpose of the study, twenty of which were amphibolites, eight schists, and two acid igneous vein material. With the exception of five amphibolites, all were garnet bearing. Special emphasis was placed throughout on the amphibolites and their constituent garnets, in view of the scarcity of well documented literature concerning garnets from this particular host type rock. The work of Crosby (1960), from the immediate area sampled, has provided an excellent framework upon which to base the investigation.

The host rock study was designed to be of a comparative nature, in order to discern similarities and dissimilarities in mineralogy, chemistry, and petrological relationships. On the basis of the data available an attempt is made to corroborate or question metamorphic grade as determined by Crosby, and to ascertain, if possible, the original nature of the rock types prior to metamorphism, particularly the amphibolites.

Full descriptions of the occurrence, form, and textural relationships are presented for all garnets studied in detail; together with partial chemical analyses for Fe_2O_3, FeO, MnO, MgO, and CaO, and refractive index and cell

parameter determinations.

In the light of these results, comparison is made of the garnet compositions of the three specific host rock types, with those recorded in the literature. Trends in compositional variation of garnet, similar to those found in pelitic assemblages by Miyashiro (1953), Lambert (1959), Engel and Engel (1960), and Sturt (1962), with prograde metamorphic change are sought for garnets from amphibolites and schists. A brief evaluation is then made of the effects of variance in bulk rock composition on that apparent in the garnets. The problem of coexistence of garnetiferous and non-garnetiferous varieties of amphibolites, is also briefly reviewed in the light of the results. Certain features suggesting instability in many of the garnets are examined, and a possible mechanism giving rise to this is sought.

With the exception of the determinations of FeO, Na_2O, and K_2O, and the complete analysis of one garnet-bearing amphibolite which were made by wet chemical procedures, all the remaining whole rock analyses were accomplished using X-ray fluorescence analytical techniques. All partial garnet analyses were determined by wet chemical means. Garnet cell parameter measurements were achieved by way of the X-ray powder photographic method, and refractive index by the conventional oil immersion technique.

LOCATION AND ACCESSIBILITY OF THE AREA STUDIED

The region from which the specimens were collected, lies within the central Kootenay Lake area of southeastern British Columbia, and encompasses some 200 square miles of terrain. The index map, Fig. 1, shows the location of the area.

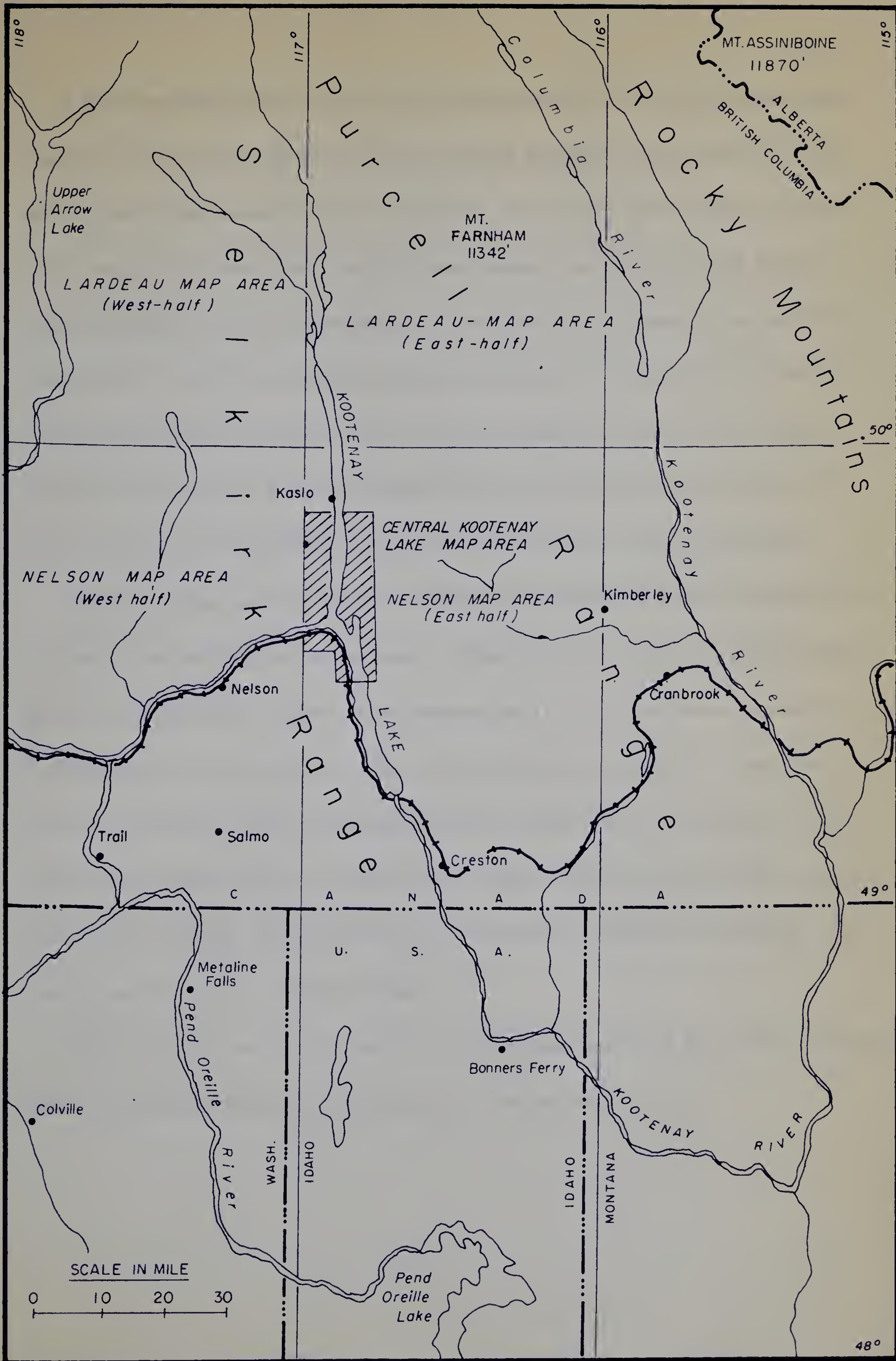


Figure1. Location map

A good paved highway (B.C. Route 3) allows ready access to the area both from the south (northern Idaho, and the Prairies by way of the Crowsnest Pass), and the west (Vancouver by way of Nelson). Two paved roads running north on either side of Kootenay Lake, many forestry roads, and the Canadian Pacific Railway fringing the southwest portion of the lake, afford ready access within the area itself. A car ferry service is operated between Kootenay Lake and Balfour. The Canadian Pacific Railway is now without passenger service in this region, and public transport to the area is possible by Greyhound bus service only, with the exception of a twice daily local bus service between Nelson and Kaslo.

Kootenay Lake, at an altitude of 1756 feet, divides the Purcell Mountains to the east, from the Selkirks to the west. Relief is of the order of 4,000 to 5,000 feet, and is especially rugged in the western part of the area, where mountains rise steeply from the lakeside. The terrain is densely covered by vegetation, conifers in the main, and overburden overlies a great deal of the ground, particularly in the lower regions. Creeks, many small cliffs flanking the lake, and road and railway cuttings, afford excellent cross-sectional exposure of bedrock. The frontispiece shows some of these aspects.

Field work was carried out mainly in a two week period in May 1964, although some restricted sampling was undertaken in late September 1963.

CHAPTER II

GEOLOGY: REGIONAL AND LOCAL

REGIONAL GEOLOGICAL SETTING

The central Kootenay Lake area, from which the specimens were collected, is a segment of a large arcuate-like structural element (convex to the east), lying on the western flank of the Purcell anticlinorium. This feature, stretching from near Revelstoke down into the State of Washington, is best outlined by a prominent limestone (the Badshot-Reeves limestone), and is appropriately termed the Kootenay arc by Fyles and Hedley (1956). The Kootenay arc itself is composed of a thick sequence of sedimentary and volcanic rocks ranging in age between earliest Cambrian and late Mesozoic, the succession becoming younger from east to west.

Extending eastwards from the Kootenay arc, across to the Rocky Mountain Trench, is a thick succession of Proterozoic rocks comprising the Windermere (youngest) and the Purcell Series. These rocks, which form the "backbone" of the Purcell Mountain Range, consist dominantly of clastic sediments. Most formations thicken westwards, and can be traced southward into the equivalent Beltian rocks of Montana and Idaho. Both series contain basic volcanic rocks, the Irene Volcanics and the Purcell eruptive rocks respectively within the Windermere and the Purcell Series. An unconformity separates the two series; the base of the Windermere being marked by a conglomerate, the Toby Formation. The duration of the erosional cycle and geographical extent of deformation are still somewhat conjectural.

To the west of the Kootenay arc lie the granitic masses comprising the Nelson and Kushanax Batholiths. These form the major part of the Selkirk Mountain Range in the south, and also parts of the southern Monashee Range. The Nelson Batholith, the bigger of the two bodies, extends areally east-west between 117° and 119° W longitude, and north-south between 49° and 50° N latitude. It is regarded as a single large composite mass, the phases of which are generally gradational. In the western margins, the Batholith contains abundant granodioritic and granitic gneisses with the foliation paralleling the trace of the body. The core area is chiefly non-porphyritic granodiorite west and south of the Castlegar region, and predominantly porphyritic granite to the east of this, with minor phases, in the order of abundance, of quartz monzonite, diorite, monzonite and syenite.

Intruding into the Kootenay arc, and extending some distance towards the east within the Windermere and Purcell, are a number of smaller granitic batholiths and stocks. These granitic masses are grouped in a curving line stretching north towards the Big Bend of the Columbia River, perhaps continuing still further north into the Precambrian of the Cariboo Mountains. Satellitic granitic bodies in the vicinity of the Kushanax and Nelson Batholiths include the Fry Creek and White Creek Batholiths to the north, the Grey Creek Stock within the area sampled, and the Bayonne Batholith, partly within and partly south of the thesis area.

For a more detailed account of the geology concerned within the general area as a whole, the reader is referred to the four reconnaissance maps (one inch to four miles) covering almost completely the area enclosed within the latitudes 49°00' and 51°00' and longitudes 118°00' and 116°00'. These include: Nelson, east-half, Rice (1941); Nelson, west-half, Little (1960); Lardeau, east-half, Reesor (1957b);

and Lardeau map-area, Walker and Bancroft (1929); with their respective geological notes.

An interesting summary of the stratigraphy and lithology of the Proterozoic of southern British Columbia and Alberta is presented by Reesor (1957a). An account of a more general nature on the igneous intrusions and related deformation in the southern part of British Columbia is given by Smith and Stevenson (1955). Cairnes (1934) offers added information on the eastern part of the Nelson Batholith, while Reesor (1958) gives a more detailed account of the White Creek Batholith. Fyles (1962) gives a short account of the geological setting of the Kootenay arc together with an account of the deformational history. Gabrielse and Reesor (1964) present a brief regional geological setting for this area.

LOCAL GEOLOGICAL ASPECTS

PREVIOUS MAPPING

Interest in the area commenced as long ago as 1825, when the mining potentialities were first brought to light by trappers who found galena showings on the site of the Bluebell mine at Riondel. This mine is still in operation today, and produces 700 tons of lead-zinc-silver ore daily.

The first comprehensive geological mapping of the area was completed by McConnell and Brock (1904). Previous reconnaissance mapping of Kootenay Lake had been carried out in 1889 by Dawson. Incorporating earlier work done by Bancroft, Walker in 1929 published a map of the Kootenay Lake area which contains essentially those stratigraphic divisions now in use. Rice in 1941

published a map on a scale of one inch equals four miles of the area contained within 49°00' and 50°00' N latitude and 116°00' and 117°00' longitude, in which the stratigraphic and structural interpretation largely aggrees with that of Walker.

A study undertaken by Crosby (1960) provides a detailed structural and petrological account of the central portion of the Kootenay arc. The extent of Crosby's map-area is outlined on Fig. 1. It contains essentially the areal limits of the sampling undertaken for this present study, and thus provides a useful base map. The geological map of the central Kootenay Lake area presented in Fig. 2 is taken from Crosby's work. The summary account of the local stratigraphy, structure and metamorphism is also largely based on his thesis.

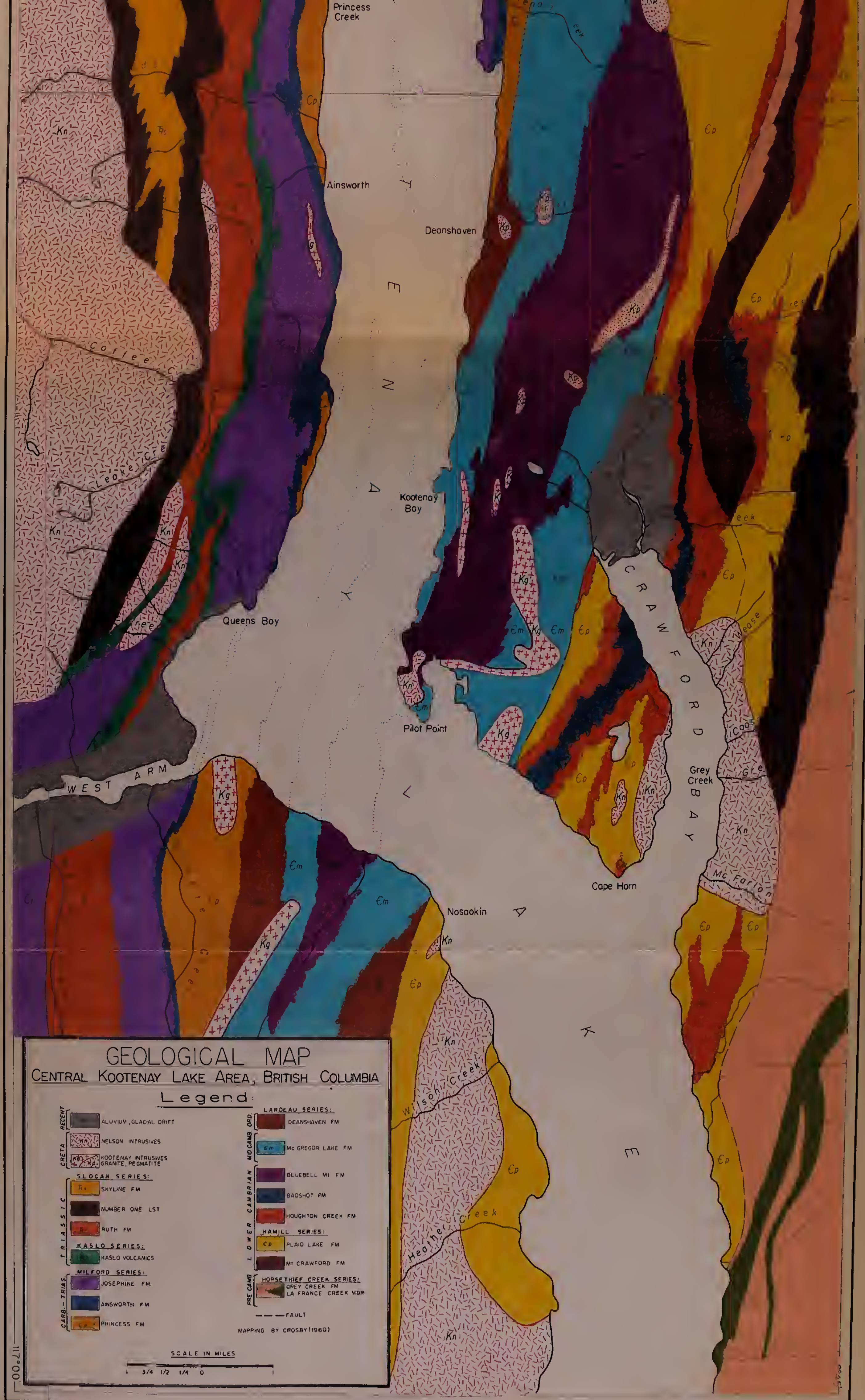
STRATIGRAPHY

The central Kootenay Lake area flanks the western extremity of the Purcell anticlinorium, and lies approximately on the point of greatest eastward convexity of the Kootenay arc. This arcuate feature is composed of a thick series of sedimentary and volcanic rocks, ranging in age from upper Proterozoic in the east to late Mesozoic in the west (against the Nelson Batholith).

At the eastern border of the map-area, the uppermost unit of the Windermere Series is exposed. This comprises the Horsethief Creek Series which consists of grey, green, and purplish slates, quartzites, and pebble conglomerate beds, and interbeds of blue-grey, crystalline, non-magnesian limestone.

Conformable overlying this series, and exposed to the west, are a varied succession of sedimentary and metasedimentary rocks belonging to the Hamill and

Figure 2. Geological map of the central Kootenay Lake area, (mapping by Crosby, 1960).


GEOLOGICAL MAP
CENTRAL KOOTENAY LAKE AREA, BRITISH COLUMBIA
Legend
RECENT
ALUVIUM, GLACIAL DRIFT
CRETA
NELSON INTRUSIVES
KOOTENAY INTRUSIVES GRANITE, PEGMATITE
TRIASSIC
SLOCAN SERIES:
SKYLINE FM
NUMBER ONE LST
RUTH FM
KASLO SERIES:
KASLO VOLCANICS
CARB.-TRIAS.
MILFORD SERIES:
JOSEPHINE FM.
AINSWORTH FM
PRINCESS FM
ORD.
LARDEAU SERIES:
DEANSHAVEN FM
MID CAMB.
Mc GREGOR LAKE FM
LOWER CAMBRIAN
BLUEBELL MT FM
BADSHOT FM
HOUGHTON CREEK FM
HAMILL SERIES:
PLAID LAKE FM
MT CRAWFORD FM
PRE CAMB.
HORSETHIEF CREEK SERIES:
GREY CREEK FM
LA FRANCE CREEK MBR
FAULT
MAPPING BY CROSBY (1960)
SCALE IN MILES
1 3/4 1/2 1/4 0 1
117°00'
Princess Creek
Ainsworth
Deanshaven
Kootenay Bay
Queens Boy
Pilot Point
WEST ARM
Nosaokin
Cape Horn
Grey Creek
CRAWFORD BAY
KOOTENAY LAKE
Coffee C.
Leake Cre
Wilson Creek
Heather Creek
Mc Farlan
Kn
Kg
Kp
Єm
Єp

Lardeau Series. The Hamill Series consists generally of a thick succession of phyllites, schists, and quartzites. Metapelites are common within the upper portion of this series. The Badshot Formation, in the lower part of the Lardeau Series, is composed of grey to cream-coloured, partly siliceous or magnesian limestone, weathering in most places to a light buff colour. Although the Badshot is relatively thin, it has proven a useful marker horizon. The Lardeau Series in general consists of slate, schist, gneiss, quartzite, and several prominent bands of magnesian limestone. Initially the Hamill and Lardeau Series were placed in the Windermere by Walker (1926). Later, however, Park and Cannon (1943) and Campbell (1947) in northeastern Washington, and Little (1960) in the Salmo area, discovered fossils in rocks considered to be equivalent to the upper Hamill and Lardeau, indicating that these series are Lower Cambrian or later in age. No fossils have been found, to date, within the area studied by Crosby or further to the north. However, severe deformation occurring in the central Kootenay Lake area, and lack of thorough field studies to the north, may account for this.

Overlying this lower Palaeozoic and upper Proterozoic succession, and separated from them by a gentle regional unconformity, is the Milford Group. This unconformity, which is marked further to the west, probably corresponds to the Cariboo orogeny. The Milford Group, occupying a belt some 5,500 feet wide along the west side of Kootenay Lake, is composed mainly of schists, with minor quartzites and limestones, and contains a conglomerate at the base. Fossils collected from near the base of the Milford are probably of Pennsylvanian age, whereas fossils collected by Cairnes (1934) from the upper sections are

probably Triassic in age. It would appear, therefore, that the Milford ranges in age between the Carboniferous and early Triassic.

Resting unconformably upon the Milford are a series of volcanic rocks, some 200 feet thick. These comprise the Kaslo volcanics which consist of intrusive as well as extrusive members. The latter are composed of fine grained flows, volcanic breccia, and tuffs, with minor interbedded sediments while the former are dark green, basic igneous rocks - in essence greenstones. Basic intrusive rocks, probably related to the Kaslo Volcanics invade the Milford and older rocks. Within the area sampled, these are dominantly amphibolites and biotite-chlorite schists, that are markedly thinner than in the northern part of the Kootenay arc. Since the Kaslo Series is bounded by sediments from which Mesozoic fossils have been collected, it is unquestionably Mesozoic, and probably Triassic in age.

Resting disconformably on the Kaslo is the Slocan Series. It consists of schist, phyllite, limestone, and minor quartzite, some 5,300 feet in thickness. Fossils collected by Cairned (1934), indicate that the Slocan Series is Mesozoic, and possibly Triassic in age. These rocks are the youngest found in the area sampled.

Crosby has subdivided the rocks within the central Kootenay Lake area into fifteen formations, and has measured "an aggregate apparent thickness" of 20,000 to 34,000 feet. A columnar section for the area, compiled by Crosby, showing the sequence and lithological character of the sedimentary and volcanic rocks, is presented in Fig. 3.

INTRUSIVE ROCKS

The intrusive rocks within the central Kootenay Lake area are considered by

Figure 3. Columnar section for the central Kootenay Lake area, (compiled by Crosby, 1960).

AGE	GRP. OR SER.	FORMATION	COLUMNAR SECT.	THICKNESS	LITHOLOGY
TRIASSIC	SLOCAN	Skyline		1500' +	DARK GREY OR BLACK PHYLLITE AND HORNFELS
TRIASSIC	SLOCAN	Number one		950'–1700'	WHITE, GREY AND BLACK BANDED LIMESTONE AND MARBLE
TRIASSIC	SLOCAN	Ruth		1500'	DARK GRAPHITIC SCHIST AND PHYLLITE WITH THIN LIMESTONE INTERBEDS
		disconformity			
TRIASSIC	Kaslo			200' +	AMPHIBOLITE AND BIOTITE-CHLORITE SCHISTS
		unconformity			
CARB.–TR.	MILFORD	Josephine		0'–2900'	MASSIVE AND LAMINATED QUARTZITES GARNETIFEROUS SCHIST THIN LIMESTONES. AMPHIBOLITE AND BIOTITE-CHLORITE SCHIST. FELDSPATHIC GNEISS
CARB.–TR.	MILFORD	Ainsworth		0'– 800'	BANDED LIMESTONE INTERBEDDED WITH PHYLLITE
CARB.–TR.	MILFORD	Princess		650'–2000'	SCHISTS AND QUARTZITES AT TOP SCHISTS AND MASSIVE LIMESTONE IN MIDDLE. MAFIC GNEISSES, SCHISTS WITH CONGLOMERATE AT BASE
		unconformity			
ORD.	LARDEAU	Deanshaven		0'-2200'	MAFIC GNEISSES. CALC-SILICATE GRANITE, MARBLE, QUARTZITE AND SCHIST
CAMBRIAN	LARDEAU	Mc Gregor Lake		1800'	CALC-SILICATE GNEISSES AND GRANULITES MARBLE
CAMBRIAN	LARDEAU	Bluebell Mt.		2500' +	FELDSPAR-QUARTZ-MICA GNEISS SCHIST AND QUARTZITE SUBORDINATE AMPHIBOLITE. LOWER PART OF FORMATION IS MISSING IN MAP AREA
CAMBRIAN	LARDEAU	Badshot		150'- 650'	WHITE MARBLE AND CALC-SILICATE GRANULITE
CAMBRIAN	LARDEAU	Houghton Creek		400' +	CALC-SILICATE GRANULITE AND LIMESTONE AMPHIBOLITE
CAMBRIAN	HAMILL	Plaid Lake		1500'–4500'	CHLORITE — BIOTITE ZONE: SILVER AND GREENISH-GREY PHYLLITE AND SCHIST GARNET ZONE AND ABOVE: MEDIUM TO COARSE GRAINED SCHIST OR QUARTZOSE GNEISS WHITE AND GREY QUARTZITES IN ALL ZONES
CAMBRIAN	HAMILL	Mt. Crawford		2700'–4000'	WHITE MASSIVELY BEDDED QUARTZITE
PRE CAMBRIAN	HORSETHIEF CREEK	Grey Creek La France Creek mbr.		3000' +	GREY OR GREENISH-GREY PHYLLITE AND SLATE. ARKOSIC PEBBLE CONGLOMERATE AND GRIT MASSIVE QUARTZITE LA FRANCE CREEK MEMBER, A BANDED GREY AND WHITE LIMESTONE

Figure 3.

Crosby (1960), to form two distinct series. The subdivision of these series is based on textural, mineralogical, and structural features. The two groups comprise the Kootenay intrusives and the Nelson intrusives, the former being regarded by Crosby as syntectonic, while the latter as post-tectonic.

KOOTENAY INTRUSIVES

The Kootenay intrusives include a varied group of generally fine grained, commonly leucocratic, small granodiorite bodies usually characterised by strong foliation and cataclasis. Aplitic material pervades much of the area of high metamorphic grade, in veins, sills, dykes, and occasionally small plugs. A minor amount of muscovite is common in these rocks. Probably more common than the aplites, and intimately associated with them, are granite pegmatites. These form sheets, concordant or approximately concordant to the foliation of the host rocks, dykes, plugs, bosses, and even small stocks. Some pegmatites display augen structure, the augen consisting of large microcline crystals.

The Kootenay intrusives are peraluminous, having notable amounts of muscovite and garnet. The intrusives, according to Crosby, are notably restricted to rocks of the staurolite zone and above. With increasing grade of metamorphism, an increasing amount of invading acid material is observed. Within the sillimanite zone, the elongate plugs and bosses characteristic of the lower grades are accompanied by a mass of injected veins, sills, and dykes. This factor coupled with the generally foliated and cataclastic nature of the Kootenay intrusives, led Crosby to the conclusion that these rocks are syntectonic.

NELSON INTRUSIVES

The Nelson intrusives, regarded by Crosby as post-tectonic, include three main areas of outcrop within the sampled region: Crawford Bay, including the Grey Creek Stock and satellitic bodies occurring near Lime Lake and on Pilot Point; the northern arm-like extension of the Bayonne Batholith on the western shore of the Lake; and the eastern extremities of the main Nelson Batholith. These intrusives are typically a series of medium- to coarse-grained, porphyritic, biotite and/or hornblende quartz monzonitesand granodiorites.

The Crawford Bay Stock and smaller associated bodies contained within the Crawford Bay promontory, are characteristically light grey, medium- to coarse-grained, commonly porphyritic, biotite granodiorites. Border zones have a tendency to be fine-grained and foliated, with no obvious reaction or replacement between the granite and the host rocks. Pegmatite dykes cut the intrusions in places.

While the main body of the Bayonne Batholith is situated just to the south of the map-area, a six mile long arm-like appendage enters the southern part of the thesis area. According to Crosby, this body contains certain features common to both main intrusive series, and consequently may be composite. The Bayonne Batholith is typically a white to light grey, medium-grained slightly porphyritic, biotite granodiorite. Contacts are gradational between the intrusive rocks and enclosing gneisses. Xenoliths, with dimensions of the order of hundreds of feet across, are common throughout, but have a tendency to be concentrated towards the contact regions. Pegmatitic dykes are common throughout the body, occurring as "massive selvages" along some of the contacts.

The Nelson Batholith, of which some sixteen square miles is exposed within the

area sampled, forms the western boundary of the map-area. The various phases of the batholith have been described by Cairnes (1934) and Little (1960). Two of the phases described are commonly met with in the area from which specimen collection was made; these being the crushed porphyritic granite, and the massive porphyritic granite members. The former is marginal and discontinuous, and is best developed to the north of Coffee Creek and on Balfour Knob, while elongate plugs between Aylmer and Queens Creek are entirely composed of this phase. The latter member, on the other hand, forms the main mass of the batholith and marginally develops a finer grained and distinctly foliated texture. A few outlying dioritic bodies occur in the neighbourhood of Woodbury Creek.

Several fine-grained melanocratic dykes and sills occur to the north of the West Arm within the metasediments. These dykes possess chilled margins and are cross-cutting. A basic sill at the Star Mine, referred to by Crosby contain xenoliths of Nelson granite, suggesting that the basic intrusives are of a later date than the batholith itself.

STRUCTURE

The major pattern within the Kootenay arc area as a whole is summarised by Crosby (1960), who presents a thorough description and structural synthesis of the local central Kootenay Lake area. Crosby envisages the structure within the latter area to be composed of a series of isoclinal folds, with axial planes characteristically dipping westward at low to moderately steep angles. The major folds, having wave lengths in the order of miles, plunge gently to the north and south away from an axial culmination in the Kootenay arc situated about the centre of the area sampled.

These folds, flanking the major structure of the Purcell anticline, are further modified by a series of normal, reverse, and minor thrust faults that are considered to be later than major folding. Two prominent faults divide the area into discrete tectonic blocks.

The attitude of major folding varies significantly along strike within the Kootenay arc. To the north of the area sampled, within the Lardeau region, folds although isoclinal as in the central area, have axial planes that dip steeply to the east and the west. In the Slocan region, at the northern extremity of the Nelson Batholith, the dominant structure is that of a recumbent anticline. To the southwest of the map-area, within the region abutting the International Boundary, the strike of vertical axial planes of isoclinal folds swings sharply westwards. It is considered that the batholithic intrusion is later than regional folding and faulting, and gives rise to only minor modification to pre-existing structures, near to some intrusive contacts.

Crosby has described in considerable detail the structural features, both major and minor, within the central Kootenay Lake area, and these will be discussed briefly. Two major faults, with an estimated stratigraphic downthrow of the order of 5,000 feet, the Crawford and the Nasookin cut the area into well defined tectonic blocks. To the east of the Crawford fault is the east limb of the Crawford Bay syncline, a broad fold with an essentially horizontal axis. In turn this rests on the western flank of the Purcell anticline. Between the Crawford and the Nasookin faults, two major folds and a number of minor ones may be defined. Occupying the central portion is the Crawford Bay syncline. Somewhat to the northwest of this is the Port Crawford anticline, while near to the southern tip of Crawford Peninsula variably plunging folds are considered to be drag folds lying on the southeast limb of

the Crawford Bay syncline. South of Crawford Peninsula, a syncline overturned to the west is speculatively suggested from shore-line mapping.

The structure west of the Nasookin fault, is composed of gently to steeply westward dipping, isoclinal folds. These isoclinal folds plunge gently away to the north and south of a regional culmination, termed the Kootenay culmination by Crosby. This feature approximately bisects the sampled area. The structures on either side of the culmination are not aligned, so that with one exception, fold axes do not coincide to the north or south.

South of the culmination, three folds are developed, the eastern most one being the Irvine Creek Anticline, then much further to the west, the Narrows Creek Syncline, and the Balfour Knob Anticline. To the north of the culmination, folding is more intense, and four folds are produced. These are the Riondel Syncline, the Ainsworth Anticline, and the Skyline Syncline. The fourth fold lying to the east of the Riondel Syncline, is the continuation of the Irvine Creek Anticline, this being the only fold having continuity across the Kootenay culmination. The eastern limb of this fold is cut by the Nasookin fault.

Effects of intrusion of the Nelson Batholith upon the regional structure are generally considered to be slight within the area sampled. However, Crosby believes that steepening and overturning to the northwest of drag folds in the northwest corner of the map-area may be related to emplacement of the batholith. Deformation as a result of batholithic intrusion, is more marked in the case of the Nelson granite to the north, as described by Hedley (1952), and about the margins of the White Creek Batholith, as described by Reesor (1958).

Minor structural features such as schistosity, slip cleavage, drag folds, lineations

of many types (including intersection of S-planes, mineral alignment, pebble elongation, and boudinage), and local jointing and faulting have been studied in detail by Crosby. These features coupled with the major folding and minor folding (including cross-folding developed sub-perpendicular to the axes of major folding and believed synchronous to development of major folding), have aided Crosby in the synthesis of tectonic events within the sampled area. Fig. 4 illustrates an attempt by Crosby to depict in three dimensions the fold pattern occurring in the central Kootenay Lake area. This diagram shows major folds, upon which are superimposed significant minor structures, including slip cleavage, drag folds, cross-folds, and boudinage.

METAMORPHISM

The wide range of rock types met within the central Kootenay Lake area, as described above, enable a thorough study of metamorphic grade to be made. Crosby (1960) has made such an investigation, the salient features are discussed in the three sections which follow. Metamorphism within the area sampled is best summarized in the words of Crosby, (abstract, p. iv);

> "Polymetamorphism has acted on many of the rocks of the central Kootenay Lake area, and a syntectonic episode of low, medium, and high grade regional metamorphism has provided the palimpsest upon which a later contact metamorphism has acted. The effects of retrograde metamorphism are widespread, and may be related to contact metamorphism around batholithic intrusions."

REGIONAL METAMORPHISM

Characteristic of the central portion of the Kootenay arc is a "localised belt" of relatively high-grade regional metamorphism (at least approaching the upper limits of the almandine-amphibolite facies of Turner and Verhoogen, 1960, p. 544). This

Figure 4. Generalised fold pattern of the central Kootenay Lake area (perspective drawing), showing structural relationships of cross folds and minor structural features including boudinage (after Crosby, 1960).

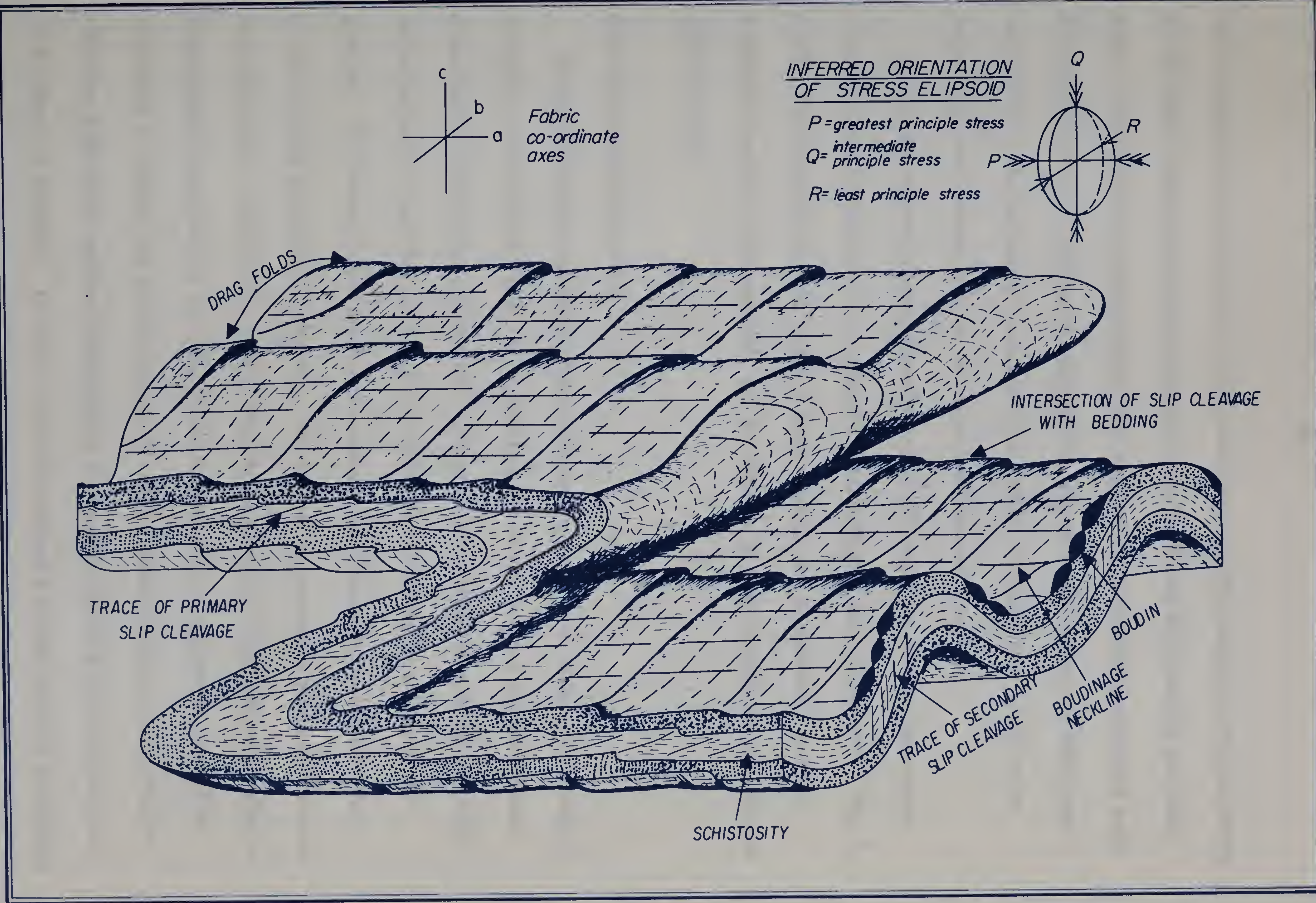

c
b
a
Fabric
co-ordinate
axes
INFERRED ORIENTATION
OF STRESS ELIPSOID
P = greatest principle stress
Q = intermediate principle stress
R = least principle stress
Q
R
P
DRAG FOLDS
INTERSECTION OF SLIP CLEAVAGE
WITH BEDDING
TRACE OF PRIMARY
SLIP CLEAVAGE
BOUDIN
BOUDINAGE
NECKLINE
TRACE OF SECONDARY
SLIP CLEAVAGE
SCHISTOSITY

Figure 4.

belt composes the central portion of the area from which the specimens were collected for this study, and continues short distance to the north and south outside the thesis area. With relatively rapid gradation, the regional metamorphism encountered away from this area has not progressed generally beyond the stage of low to middle greenschist facies. The episode of regional metamorphism is regarded by Crosby to be syntectonic, and consequently is related to the Kootenay intrusives.

Crosby has erected isograds (after Barrow, 1912) based on the first appearance of certain index minerals within regionally metamorphosed pelitic sediments. Fig. 5, p. 27 , illustrates the surficial trace of these isograds, which delineate zones of progressive regional metamorphism, and the relation of these isograds to the intrusive granitic masses.

CONTACT METAMORPHISM

Imrpinted upon the regional metamorphic pattern, are local contact metamorphic aureoles, considered by Crosby to be effective for an approximate annular distance of generally no more than half a mile. Contact metamorphism is regarded by Crosby to be the result of post-tectonic intrusion of the Nelson Batholith and satellitic granites. The Nelson Intrusives produce variable but limited deformational effects on pre-existing syntectonic structures. The contact metamorphism produces a marked hornfels aureole, which in the cases of the Nelson and Grey Creek granitic bodies is superimposed upon rocks in the chlorite and biotite zone of regional metamorphism. According to Crosby, the possible effects of contact metamorphism are indistinguishable from high grade regional metamorphism in the rocks abutting the north west arm of the Bayonne Batholith. However, the writer noticed a marked effect of hornfelsing

in amphibolites in the vicinity of this granite. Further discussion of this will be found in the following chapter.

RETROGRESSIVE METAMORPHISM

Mention of certain retrogressive metamorphic effects has been made by Crosby. These are especially noticeable within parts of the Ruth Formation of the Slocan series, where regional metamorphism has reached staurolite grade. There, staurolite is partially, and in certain rocks probably completely, altered to sericite and chlorite. Garnets are enveloped to varying degrees by chlorite.

Outside the contact zone, phyllites and schists of the Slocan series abutting against the Nelson Batholith, lie in the biotite zone. From petrographic studies, Crosby dismisses the premise that these rocks were once of a higher grade, since no trace was found by him of relict textures.

AGE RELATIONSHIPS OF INTRUSIVE PHASES AND METAMORPHISM

Nelson plutonic rocks were assigned by earlier workers to the Jurassic, in view of their similarity to those of the Coast Range, which at this time was considered Jurassic. However, later evidence showed the main body of the Coast Range Plutonic rocks to be probably of Lower Cretaceous age. Cairnes (1934), and later Rice (1941), both favoured a Cretaceous age for the Nelson plutonic rocks. However, as Little (1960, p. 86) points out, stratigraphic evidence is very slim for the exact establishment of the age of these intrusive rocks. The lower limit according to Little, that can be stated with any confidence is post-Middle Jurassic. This is based on the fact that the Hall Formation, the youngest fossiliferous strata known to

be cut by the Nelson mass, is of early Middle Jurassic age. It is to be noted that the fossiliferous horizon upon which this evidence is based is overlain by at least a few hundred feet of sedimentary and possibly volcanic rocks, which so far have not yielded fossils. These non-fossiliferous rocks are also cut by the Nelson granitic body.

There is variable stratigraphic evidence for the upper limit of the Nelson granite. Within the area mapped by Little (1960), the Sophie Mountain Formation unconformably overlies the Rossland Formation, and also possibly serpentinites that intrude the Rossland and are cut by the Nelson granite. According to Little, the Sophie Mountain Formation contains fossil flora probably Upper Cretaceous but possibly early Tertiary. The Sophie Mountain Formation also contains granite pebbles that may conceivably be derived from the Nelson granite. This evidence would suggest the range of age for the Nelson intrusion to be at least mid-Jurassic to late Cretaceous.

Further, somewhat controversial evidence is to be found in the sedimentary history of the Rocky Mountains to the east. The Kootenay Formation, the basal beds of which contain fossils of Portlandian age (late Upper Jurassic), do not contain detrital feldspar. Within the Blairmore Formation however (lower age being Aptian, or questionably Barremian, feldspar is abundant above the basal beds. The basal sections of the Blairmore contain conglomerates, which indicate according to Warren (1951), pronounced uplift to the west of the Trench. A study by Anderson (1951) of the McDougall-Segur conglomerate in the upper part of the Blairmore, has indicated that granite, granophyre, and various porphyritic igneous intrusives were exposed during the deposition of the conglomerate. This evidence has resulted

in some workers concluding that the Nelson granite is pre-Lower Cretaceous in age. Further evidence in support of this idea has been suggested by Beveridge and Folinsbee (1956), who contend that the pebbles from the McDougall-Segur conglomerate contain a heavy mineral suite similar to that of the Nelson granite. Smith and Stevenson (1955) have reviewed the possibility that these granite pebbles within the Blairmore are derived either from the Nelson rocks or from sills within the Purcell Series. They note that granophyric rocks are common neither to the Coast Range nor to the Nelson intrusives. Apparently on these grounds they dismiss such an origin for the pebbles, advocating instead that they are Purcell derived. However, Norris et al (1965) have recorded K-Ar whole rock ages ranging between 113 and 174 m.y. for igneous pebbles from the McDougall-Segur conglomerate. This, therefore, dismisses a Purcell origin for these pebbles.

Crosby favours a mid-Cretaceous age for the Nelson intrusives, on the grounds of a 105 m.y. date by Beveridge and Folinsbee (1956) on a zircon from this granite, and an identical date for the Idaho Batholith by Larsen (1956).

Relatively recent radiometric age dating on the Nelson and "satellitic" granites, demonstrates well the complexity of the history of these bodies. Gabrielse and Reesor (1964) have compiled data obtained by the Geological Survey of Canada from the granites of southeastern British Columbia. They have recorded K-Ar ages ranging between 171 and 49 m.y. for the Nelson Batholith alone. Those for the "satellitic" granites are equally as scattered. The White Creek Batholith, for example, ranges in age between 82 and 18 m.y. by K-Ar methods, while a whole rock Rb-Sr isochron plot for the same granite, yields an age of 90 m.y. The K-Ar dates for the Bayonne Batholith also vary considerably,

ranging between 110 and 25 m.y. No dates are available for the Grey Creek Stock.

Geological evidence would suggest that there have been at least two metamorphic phases involved in the Kootenay arc, but in view of the currently limited knowledge (both geological and geochronological) concerning the area as a whole, it is exceedingly difficult to relate these phases in terms of the history of the Nelson granitic rocks. Crosby has rejected the idea that the "belt" of high-grade metamorphic rocks of the central Kootenay Lake area are related to the Shuswap Terrane. His basis for this conclusion stems from the fact that supposedly Carboniferous and younger sedimentary rocks overlie with "apparent conformity" older rocks, both of which appear to be involved in the same metamorphism. Instead, Crosby has related this "belt" to a syntectonic event prior to the intrusion of his so called "Nelson Intrusives". These latter rocks, which Crosby considers to be post-tectonic, have subsequently imprinted relatively narrow hornfelsed contact aureoles upon this regional metamorphic phase.

Unfortunately, age dating work on the Kootenay Lake metasediments is decidedly sparse. To the writer's knowledge, only three K-Ar dates are available (Baadsgaard, personal communication). These include a determination on hornblende from an amphibolite boudin between Kootenay Bay and Crawford Bay on B.C. Highway 3, and muscovite and biotite determinations from the enveloping gneiss. The hornblende gave an age of about 120 m.y. while the muscovite and biotite ages are both about 50 m.y. Although thirteen minerals (six biotite, six muscovite, and one hornblende) together with appropriate whole rock samples, were separated by the writer for Rb-Sr and K-Ar determinations at the University of Oxford, the results of these

are as yet unavailable.

It is proposed by the writer to adopt the metamorphic picture envisaged by Crosby, regarding the central Kootenay Lake area, pending further more complete geological and geochronological data concerning the intrusive and metamorphic history of this area.

CHAPTER III

THE AMPHIBOLITES, SCHISTS, AND ACID IGNEOUS VEINS: MINERALOGICAL AND CHEMICAL ASPECTS

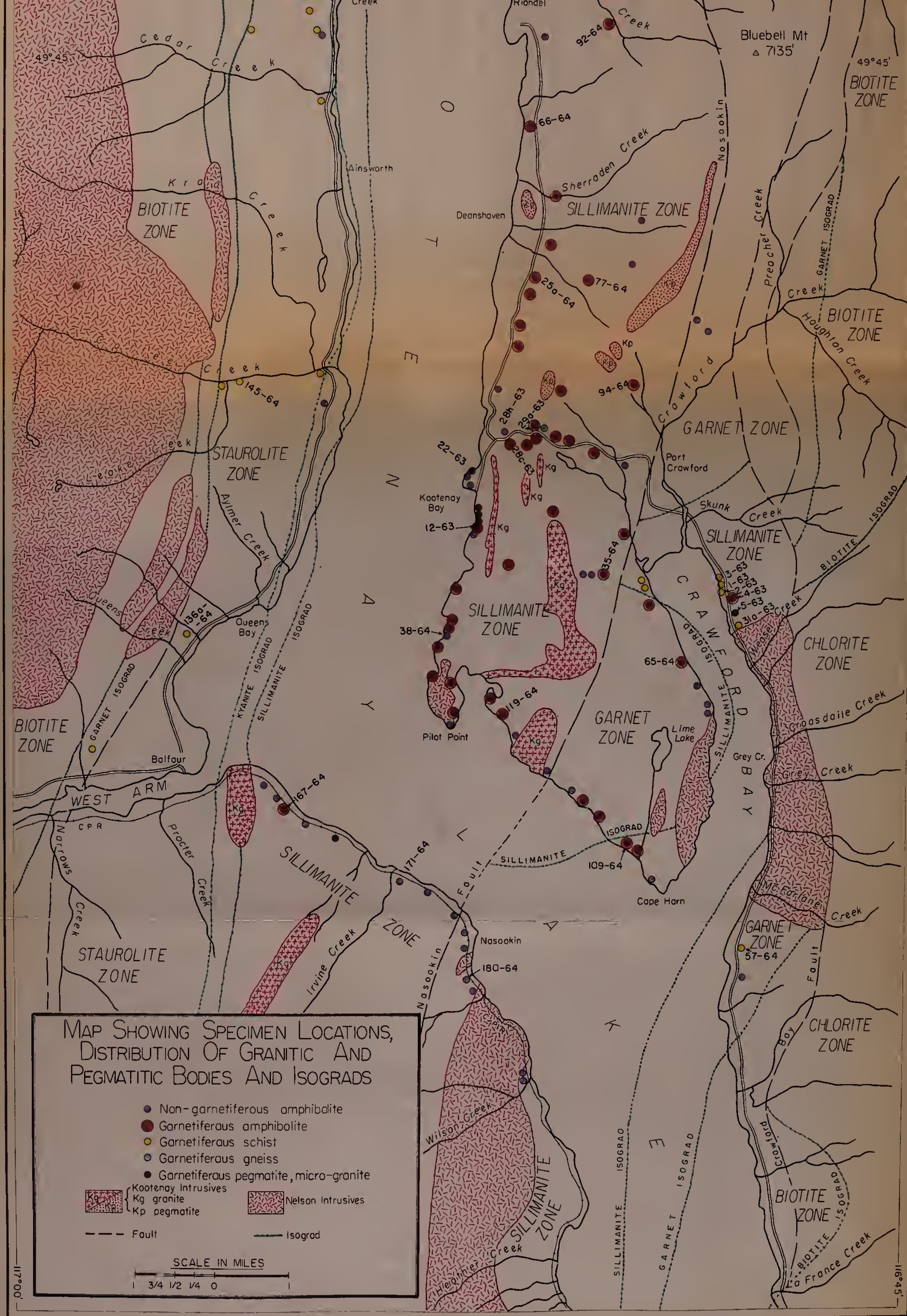
SAMPLING PROCEDURE

It should be pointed out that at the time specimen collection was made, the writer was unaware of Crosby's (1960) mapping; thus sampling was made without prior knowledge of the detailed geology of the area. It is merely fortuitous that the extent of the area sampled almost coincides with Crosby's map.

Sampling was made on a geographical basis, with the intention of obtaining the best possible coverage of the area, both perpendicular and parallel to general regional strike. However, certain limitations were imposed upon this pattern of sampling, such as non-uniform distribution of garnet-bearing rocks (especially the amphibolites), overburden and vegetation, and at higher elevations, the spring snow-line. As a result the geographical uniformity of sampling was not always strictly adhered to, and obvious gaps appear in the proposed pattern. Paved and forestry roads, railroad cuttings, and creek and lake shore outcrops, provided some excellent cross-sectional geological exposures. These furnished, in the main, the locations from which the specimens were collected.

Some thirty specimens were singled out for study, mainly on the basis of areal distribution. These included twenty amphibolites (fifteen garnet-bearing, and five without garnets), eight garnet mica schists, and two garnet-bearing acid igneous veins. Fig. 5 illustrates the location of all garnet-bearing specimens collected,

Figure 5. Map showing specimen location, distribution of granitic and pegmatitic bodies, and isograds.



Map Showing Specimen Locations, Distribution Of Granitic And Pegmatitic Bodies And Isograds
Non-garnetiferous amphibolite
Garnetiferous amphibolite
Garnetiferous schist
Garnetiferous gneiss
Garnetiferous pegmatite, micro-granite
Kootenay Intrusives
Kg granite
Kp pegmatite
Nelson Intrusives
Fault
Isograd
SCALE IN MILES
3/4 1/2 1/4 0
KOOTENAY LAKE
CRAWFORD BAY
WEST ARM
BIOTITE ZONE
GARNET ZONE
SILLIMANITE ZONE
STAUROLITE ZONE
CHLORITE ZONE
GARNET ISOGRAD
SILLIMANITE ISOGRAD
KYANITE ISOGRAD
BIOTITE ISOGRAD
Bluebell Mt
7135'
Riondel
Deanshaven
Ainsworth
Kootenay Bay
Port Crawford
Pilot Point
Queens Bay
Balfour
Nasookin
Cape Horn
Lime Lake
Grey Cr.
CPR
Fault
Cedar Creek
Kraid Creek
Lelake Creek
Aylmer Creek
Queens Creek
Procter Creek
Narrows Creek
Irvine Creek
Wilson Creek
Sherraden Creek
Preacher Creek
Houghton Creek
Skunk Creek
Crawford Creek
Croasdaile Creek
Grey Creek
McFarlane Creek
La France Creek
Nasookin
Kg
Kp
92-64
66-64
25a-64
77-64
94-64
28h-63
29a-63
28c-63
22-63
12-63
35-64
38-64
119-64
65-64
109-64
145-64
136a-64
167-64
171-64
180-64
57-64
3-63
1-63
24-63
5-63
31a-63
49°45'
116°45'
117°00'

Figure 5.

and includes also the location of non-garnetiferous amphibolites. Specimens used for this study are marked with their appropriate sample number. The plotting of the location of these specimens was made by the use of pace and compass methods, and aided partly by aerial photographs.

OCCURRENCE OF AMPHIBOLITES, SCHISTS, AND ACID VEINS

AMPHIBOLITES

Amphibolites are fairly abundant throughout the sampled area, particularly within the Lardeau Series, and certain horizons within the Milford and Kaslo Series. The majority of the amphibolites sampled were from the Lardeau Series within the Houghton Creek, Bluebell Mountain, and McGregor Lake Formations. These include both garnet-bearing and non-garnet-bearing varieties of amphibolites - the latter probably being the most numerous. The occurrence of the two varieties of amphibolites, in close association with one another poses an interesting question as to the mechanism of garnet paragenesis in amphibolites as a whole. This is discussed in somewhat greater detail in a later section (p. 116). Biotite-rich varieties of amphibolites appear to be particularly abundant in the vicinity of the northern extension of the Bayonne Batholith.

The majority of amphibolites of interest are massive, well jointed, and exhibit a variety of forms. These range from "pod-like", lenticular, and "barrel-shaped" bodies (undoubtedly boudins), to broken, somewhat beaded, and seemingly continuous bands (possibly incipient boudins). The size of these bodies is also exceedingly variable. Some amphibolites in the Houghton Creek and Bluebell Mountain Formations may be hundreds of feet thick. In many other cases, the

thickness ranges from one to approximately thirty feet. The length-wise continuity of these bodies is often difficult to discern in the majority of cases seen by the writer (save for the much smaller boudins). This is due to the poorness of outcrop, or where outcrop is available, lack of adequate cross-sections exposing three dimensional aspects of the bodies.

It is interesting to note that the general alignment of minerals, especially acicular hornblende, follows that of the enclosing metasedimentary rocks and internally outlines the shape of the amphibolite bodies. Relatively good sections of these amphibolites are visible in road cuts on B.C. Highway 3 between Kootenay Bay and Crawford Bay, along certain sections of the lake shore, around the Crawford Peninsula, and in the middle sections of Tam O'Shanter Creek. Plates 1 and 2 illustrate some of the morphological features of the amphibolites.

Boudinage, which is considered by Cloos (1947) to be caused by elongation and extension of competent beds between incompetent beds, is consistently exhibited by amphibolites within the area sampled. In every case, according to Crosby, the neckline of boudinage plunges down dip in the enclosing metasedimentary rocks parallel to the axes of the cross-folds or rolls (ie. parallel to the "a" fabric axis). Fig. 4 illustrates diagrammatically the relationship envisaged between boudins and major and minor structural features. The formation of boudins with necklines parallel to the "a" axis, has been reported elsewhere (Rast, 1956).

The metasedimentary rocks that enclose and generally abut against the amphibolites, are variable from formation to formation. Within the Houghton Creek Formation, these predominantly compose calc-silicate granulites, with minor amounts of mica schists, while in the Bluebell Mountain Formation, the dominant enveloping

PLATE 1

FIELD PHOTOGRAPHS OF THE KOOTENAY LAKE AMPHIBOLITE BODIES IN ROAD SECTIONS ALONG B.C. HIGHWAY 3, BETWEEN KOOTENAY BAY AND CRAWFORD BAY

a) Concordant garnetiferous amphibolite body, lower center, enveloped by biotite augen gneisses of the Bluebell Mountain Formation. Body tapers to the right. Gneisses pervaded by "sweats" of coarse pegmatitic material, above and below (to the right) the amphibolite body. Hammer (3 foot shaft) for scale, lower right.

b) Small, non-garnetiferous amphibolite boudin, set in finely banded calc-granulites of the McGregor Lake Formation.

c) Thin, concordant, garnetiferous amphibolites, "wedged out" in the biotite gneisses of the Bluebell Mountain Formation. Hammer indicates the position of the body. Gneisses contain abundant pegmatitic material, as "sweats", veins, and stringers.

d) Concordant, garnetiferous amphibolite, showing termination (centre), with shallow, pegmatite filled re-entrant. Amphibolite enveloped by biotite augen gneisses of the Bluebell Mountain Formation. Gneisses invaded by abundant pegmatitic material (N. B. particularly, top left corner of photograph).

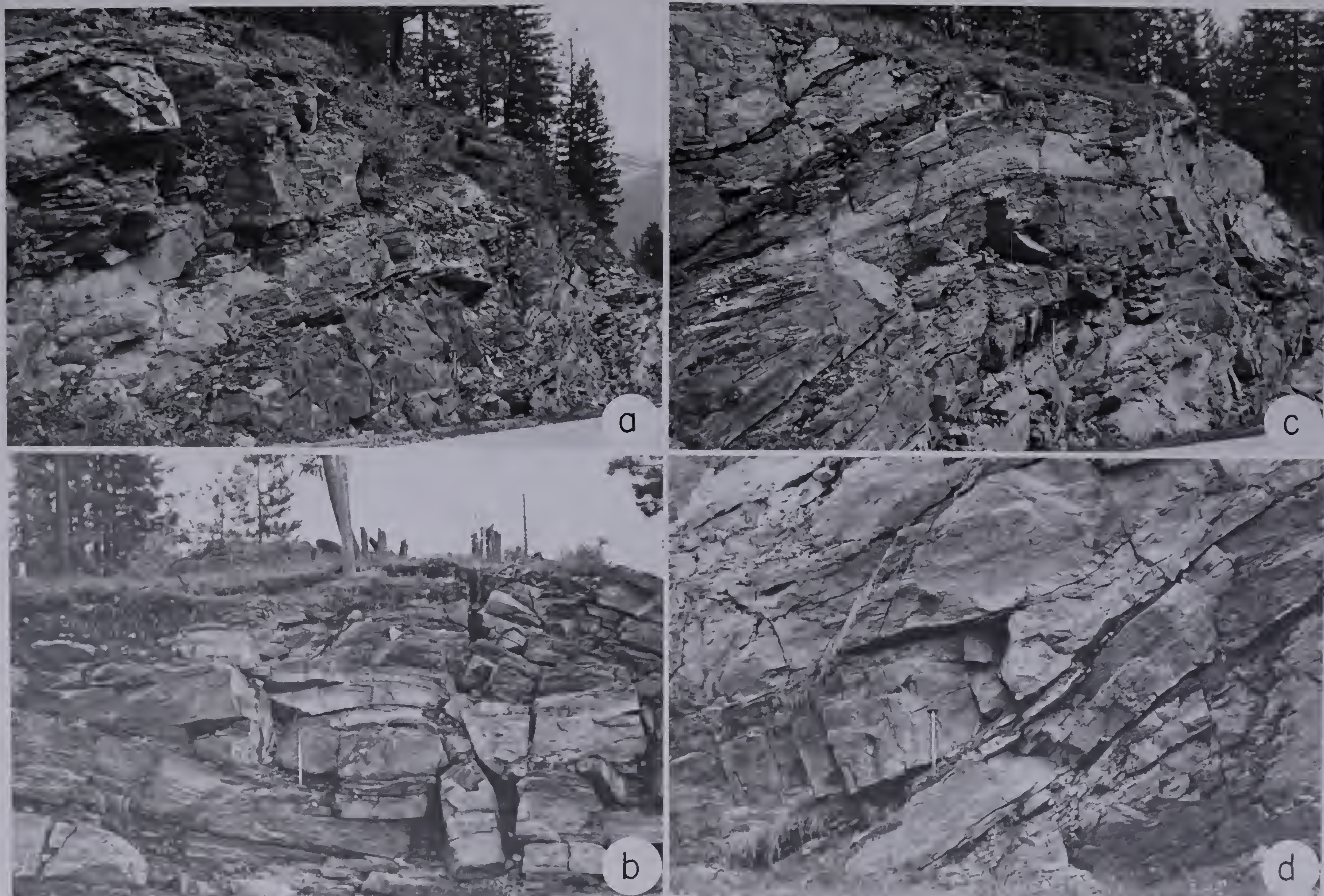


PLATE I.

PLATE 2

FIELD PHOTOGRAPHS OF THE KOOTENAY LAKE AMPHIBOLITE BODIES, IN ROAD SECTIONS ALONG B.C. HIGHWAY 3 BETWEEN KOOTENAY BAY AND CRAWFORD BAY, AND ON LAKE-SHORE SOUTH OF KOOTENAY BAY

a) B.C. Highway 3, road section. Garnetiferous amphibolite boudin, enveloped by biotite gneisses of the Bluebell Mountain Formation. Metasedimentary rocks are cut by aplite and pegmatite veins. Hammer (3 foot shaft), in centre of photograph, for scale.

b) B.C. Highway 3, road section. Garnetiferous amphibolite body left, enveloped by gneisses of the Bluebell Mountain Formation. Note the intense injection by both aplitic and pegmatitic material; centre and to the right in the photograph. Aplite at the mid-right edge of the photograph, contains small xenoliths of metasedimentary material. Both aplites and pegmatites carry garnet.

c) B.C. Highway 3, road section. Closer view of the garnetiferous amphibolite body, shown in (a) of this plate. The neck and partition between boudins, is visible at the centre of the photograph. Small quantities of quartz-rich material, infils segments in the partition area.

d) Lake-shore section, south of Kootenay Bay. Non-garnetiferous amphibolite boudin, at the centre of the photograph, enveloped by biotite and hornblende gneisses of the Bluebell Mountain Formation, and cut by fine grained granitic material, right centre.

PLATE 2.

metasedimentary rocks are biotite-gneisses. Higher still in the sequence, within the McGregor Lake and Deanshaven Formations, the host rocks to the amphibolites are predominantly calc-granulites with minor biotite gneisses and schists.

SCHISTS

Of the eight garnet-bearing schists studied, three were collected from the west side of Kootenay Lake, north of the West Arm (two from the Ruth Formation, and one from the Princess Formation), four from the Houghton Creek Formation north of the Grey Creek Stock along B.C. Highway 3, and one from the Plaid Lake Formation, south of this body along the same highway. All the latter five specimens are probably within the confines of the contact aureole about the Grey Creek Stock.

In the majority of cases, these schists compose relatively thin intercalations within arenaceous, and in some instances, calcareous sequences.

ACID IGNEOUS VEINS

As was previously mentioned, the Kootenay Intrusives have notable peraluminous affinities, and contain abundant muscovite and garnet. These intrusives abound in the central higher grade "belt" previously described. The writer has noted strong evidence for assimilation in certain of these aplitic dykes, and consequently would attribute, at least partly, the abundance of garnet in these rocks to the incorporation of metasedimentary material.

Two specimens were collected from these intrusives, and both contained abundant garnet. One was obtained from a massive pegmatite vein within the

Houghton Creek Formation, near to the contact of the Grey Creek Stock. The other was from an aplite vein cutting the upper Lardeau located at the northern extremity of the small promontory north of Kootenay Bay.

COMPOSITION AND TEXTURE OF AMPHIBOLITES, SCHISTS, AND ACID IGNEOUS VEINS

The amphibolites are typically fresh, dark-green to black, well lineated, massive, medium grained hornblende-plagioclase rocks, with variable amounts of quartz, biotite, garnet, opaque minerals, and sphene. Hornblende composes well over half (volume per cent) of the rocks, with plagioclase (typically andesine) occurring in variable amounts approximately between 10 and 20 volume per cent. Quartz is notably an abundant mineral also, but generally subordinate to plagioclase. On the whole, as was mentioned previously, it would seem that garnet-bearing amphibolites are less numerous than the non-garnetiferous varieties. However, in spite of the presence or absence of garnet, both these varieties appear to be remarkably similar in such characteristics as colour, form, mineralogy, and texture.

The schists studied in detail are more variable. Quartz is omnipresent, and composes between 30 and 70 volume per cent of these rocks. The schists contain predominantly two micas, biotite and muscovite, which collectively comprise some 20 to 40 per cent. In three out of the five cases studied in detail, muscovite predominates over biotite. Chlorite is abundant in the two specimens from the Ruth Formation where retrograde metamorphism is prominent, and in one specimen, has a modal content of 20 per cent. It is absent in the remaining cases.

Plagioclase is generally minor in occurrence throughout, although one specimen contains as much as 10 per cent by volume. Garnet is present in all specimens, and is variable in amount, while staurolite occurs in only one of the rocks examined. A sample collected from the immediate vicinity of the Grey Creek Stock contact, carried the only sillimanite (mainly as fibrolite) seen by the writer, within the area. Accessories include opaque minerals, apatite, tourmaline, and the occasional zircon.

The two samples of acid igneous vein material examined comprise a buff coloured aplite vein, and a relatively coarse-grained pegmatite. Both consist of quartz, albite, microcline, muscovite, and garnet.

MINERALOGY

MODAL ANALYSES

Modal analyses of eighteen amphibolites and five garnet mica schists were made on unstained sections, approximately 3/4" by 1 1/4" in size. These sections were cut as near as possible perpendicular to the strongest lineation or schistosity for maximum efficiency. Counts were made of 2,000 points - the maximum number of the range suggested by Chayes (1956, p. 89-91). This number of counts may at first appear excessive, especially in the case of the amphibolites, where grain size is relatively homogeneous. However, the porphyroblastic garnets, although appearing relatively homogeneous in many instances, are upon closer examination, somewhat unevenly distributed. This may be readily demonstrated, when the totals after 500, 1000, 1500 and 2000 point counts are recorded, as shown for two garnet-bearing amphibolites in

Table 1.

In certain instances, it was necessary, as has been suggested by Shaw (1955, p. 615-6), to make visual estimates of the mode of large porphyroblastic minerals, from polished slabs of the hand specimens. These cases are marked by asterisks in tables of modal analytical results.

Grain counting was accomplished, using a Swift Automatic Point Counter and Stage. Distances between centers counted were 0.3 mm. and traverses spaced 0.3 mm. apart. The results of modal analyses of amphibolites are recorded in Table 3 and those for schists in Table 5.

Table 1. Modal analyses of two garnet-bearing amphibolites to show fluctuations produced particularly in garnets at counting intervals of 500, 1000, 1500, and 2000 points.

	Specimen 92-64				Specimen 167-64			
	500	1000	1500	2000	500	1000	1500	2000
Quartz	5.7	9.8	8.4	7.3	13.0	12.3	13.1	12.7
Plagioclase	15.7	15.7	15.3	15.8	15.6	13.8	13.5	12.6
K-Feldspar	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
Hornblende	69.8	59.0	64.0	65.6	54.2	57.3	60.2	61.6
Garnet	1.2	7.5	5.5	5.1	10.4	9.3	7.1	7.3
Biotite	.8	.9	1.0	.8	2.2	2.4	1.9	1.9
Op. minerals	2.0	2.4	2.2	1.8	1.0	.8	.7	.8
Sphene	2.6	1.9	1.6	1.8	1.0	1.6	1.5	1.3
Apatite	.8	1.0	.8	.7	.4	.4	.4	.5
Epidote	-.-	.1	.1	.1	.2	.1	.1	.1
Sericite	1.4	1.5	1.0	.9	1.2	1.4	1.1	.9
Chlorite	-.-	-.-	-.-	-.-	.8	.6	.4	.3
Calcite	-.-	.2	.1	.1	-.-	-.-	-.-	-.-
Tourmaline	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
Totals	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

MINERALOGY OF THE AMPHIBOLITES

Hornblende, ranging in modal content between 55 to 75 volume per cent, generally forms stubby to occasionally rather slender lath-like, grains. Basal sections are found in most thin sections, and many of these show approximately idioblastic outlines. In many instances, hornblende laths have exceedingly ragged or corroded terminations. Grain size of hornblende is generally quite uniform, ranging from 0.5 to 1.5 mm. Specimen 28h-63 is probably the coarsest grained, and stout laths up to 4 mm. in length occur. An amphibolite collected from the vicinity of the northern extension of the Bayonne Batholith, has a hornfelsic texture, with the hornblende grains averaging 0.3 mm. Pleochroism is well marked, and varies from,

X - pale yellow green, Y - olive-green, Z - dark green

to X - greenish brown, Y - reddish brown, Z - red brown.

Two non-garnetiferous amphibolites, specimens 38-64 and 171-64 contain a decidedly bluish tint in the direction of maximum absorption. Colours for the maximum absorption of hornblende in all specimens studied are recorded in Table 7. In several instances, predominantly brown and ragged hornblende contains narrow pleochroic, pale green borders. Maximum extinction angles ($c \wedge Z$) measured, range between 20 and 26 . Hornblende on the whole is fresh and remarkably free from inclusions. Included minerals, where present, are predominantly minute quartz granules, but are usually accompanied by minor opaque minerals and the occasional idioblastic apatite grain. Even where laths have corroded terminations, the cores are surprisingly unaltered. Hornblende

twinning is present, but is generally rare. Biotitic alteration of hornblende is comparatively uncommon, but is seen in two amphibolites (specimens 28c-63 and 28h-63). In these two rocks, orange brown biotite has developed both peripherally, about markedly corroded hornblende laths, and somewhat less frequently, along cleavage traces. In the vicinity of garnet porphyroblasts, there is occasionally a minor development of a weak pleochroic pale green hornblende. This colour is similar to that found in the margins of certain brown hornblendes, mentioned above.

Plagioclase occurring in the amphibolites varies in modal content between 7.0 and 19.0 per cent, and although typically andesine in composition, ranges from sodic andesine to calcic labradorite. Grains are invariably xenoblastic, usually stubby, rounded, equant or lath-like, and occur either as isolated grains or in clustered groups, occasionally somewhat interlocking in habit. Size of grains are highly variable within individual specimens, but are generally comparable from specimen to specimen, averaging between 0.3 and 0.7 mm. Albite twinning is the most prevalent type, but a combination of Carlsbad and albite is also common together with some Carlsbad and more infrequently pericline twinning. Untwinned grains are also common. Save for granular epidote, present as minute inclusions, the plagioclases are generally quite free from included minerals. Sericitic alteration of plagioclases, although exceedingly variable in degree, is universally present. Specimen 65-64 shows by far the most marked degree of sericitisation, whereas in many specimens, plagioclase is relatively fresh, being affected in certain rocks only where late minute, quartz-filled

fractures occur. Although staining of sections was not undertaken, no obvious potash feldspar was recognised.

Quartz is notably present in all the amphibolites studied in detail, ranging between 0.5 and 13.5 per cent in modal content. Grain size and shape are exceedingly variable. Quartz is generally rounded to subangular, elongate, and may occur both as isolated grains, as well as clusters of almost equigranular grains, mosaic patchworks of minute granules, stringers, lens-shaped patches, in minor instances as included pools within plagioclase, and also as myrmekitic intergrowths. Undulose extinction abounds in the majority of specimens examined.

Biotite, although conspicuously present in some amphibolites, is trivial in amount or non-existent in others. Its occurrence may partly be due to the introduction of K_2O (potash metasomatism?), since the abundance of biotite appears to be somewhat directly related to the amount of acid igneous material pervading both the enclosing metasedimentary rocks, and in some instances, the amphibolites themselves. Modal content varies from 0.1 to 6.2 per cent within the biotite-bearing specimens studied. Grain-size, although variable, is usually small, ranging between 0.1 (or much smaller) and 0.5 mm. Biotite consists of fresh, stout to very slender, moderately ragged to well formed flakes. The flakes are in general randomly oriented, and in many rocks are clustered in groups. Biotite is in most cases strongly pleochroic; Z - orange brown (on occasion reddish-brown), X - pale straw yellow. Two amphibolites (specimens 38-64 and 180-64) contain biotite having notably different pleochroic schemes; Z - dark (vandyke) brown, to X - pale brownish yellow. Biotite is invariably associated with garnet porphyroblasts, where it occurs as randomly oriented mainly small flakes, generally

growing peripherally and within this mineral. In many instances biotite occurs scattered sporadically throughout the rock as isolated flakes or in clustered groups, or as has been mentioned previously, apparently replacing hornblende.

Of the accessory minerals, sphene and opaque minerals are by far the most abundant. Sphene with one exception (that of the hornfelsed amphibolite, specimen 180-64, where it is completely absent) is ubiquitous, ranging in modal content between 1.2 and 6.0 per cent. Sphene is variable in size, from minute granules to grains of 0.6 mm. in length. Although generally xenoblastic, idioblastic wedges, usually very small, occur on occasion. Sphene generally forms both as isolated grains and as aggregates of grains comprising mosaics of drop-like or pellet shaped granules, occasionally lace-like patchworks of minute granules, and somewhat thin and beaded stringers of granules. In larger grains, the parting parallel to 221 is prominent, and weak pleochroism can be discerned which is pale brown to pinkish brown in colour. Sphene, to varying degrees, rims opaque minerals, in the majority of the amphibolites examined.

No attempt was made to distinguish between the opaque minerals. They have consequently been combined as one group alone, comprising ilmenite and magnetite. These minerals are invariably present and range in amount from 0.1 to 5.8 per cent. They occur as rounded, subangular, occasionally ragged, but rarely lath-like grains. Grain size is exceedingly variable, generally ranging from minute grains up to 0.4 mm.; occasionally grains occur up to 1.0 mm. Opaques generally form as isolated grains, as well as grain aggregates. The odd amphibolite contains hornblendes peripherally bordered by finely divided ore specks. These hornblendes also contain specks of opaque minerals along

cleavage traces. The opaques are invariably associated with sphene, and sometimes are marginally altered to hematite.

Apatite is an ubiquitous accessory, ranging in modal content from 0.1 to 1.3 per cent. It usually occurs as isolated idioblastic hexagons, slender needles, and as xenoblastic granules, but occasionally clusters in groups.

Epidote sporadically occurs as colourless to very pale yellow xenoblastic small granules. In some instances, it is faintly pleochroic. It ranges modally from trivial amounts to 0.4 per cent, and is invariably included within plagioclase. In one amphibolite (specimen 94-64), minor epidote was observed to rim sphene granules, adjacent to plagioclase. Occasionally it is associated with garnet.

Chlorite is generally uncommon, being completely absent in all non-garnetiferous amphibolites examined in detail. Where present in garnetiferous amphibolites, it forms isolated flakes, small mats and rarely veinlets of randomly oriented minute flakes. Flakes are faintly pleochroic green, and show pronounced "Berlin blue" interference colours, under crossed nicols. Generally where present, it is associated with garnet porphyroblasts, but there is also minor occurrence peripheral to hornblende laths.

Calcite is sporadically present in the garnet-bearing amphibolites examined. In one specimen in particular, (109-64), modal content is 1.4 per cent. Calcite is both present in isolated grains and in aggregates of several grains, generally in the immediate proximity of garnet porphyroblasts or interstitially between hornblende laths. It ranges in size up to 1.0 mm.

Tourmaline is rare, but where present, it occurs as minute granules and needles in trivial amounts.

MINERALOGY OF THE SCHISTS

Quartz varies substantially in modal content in the schists examined in detail. It forms both as isolated grains, and as aggregates of grains, varying in shape from rounded to simply sutured, lenticular to rectangular (ribbon-like). Grain size, even within individual schists is highly variable, although within schists from the Ruth Formation (specimens 136a-64 and 145-64) grain size has a tendency to be rather uniform throughout. Undulose extinction is abundant and is prominent particularly in schists (specimens 1-63 and 2-63), where the quartz grains have been strongly deformed during "microfolding".

Plagioclase is generally minor except in one schist where a modal content of 10.3 per cent has been recorded. In the schists collected from north of the Grey Creek Stock, particularly 1-63 and 2-63, plagioclase is somewhat corroded (almost spongy) in appearance, and generally confined to the vicinity of garnet porphyroblasts. Plagioclase occurring elsewhere, is generally equant, and usually relatively uniform in size. Of the twinning observed, albite is by far the most common type, although minor albite-Carlsbad, occasionally Carlsbad, and very minor percline twinning, are also present. Untwinned plagioclase is also relatively common. Sericitic alteration of plagioclase is almost invariably present, although not excessive in any particular instance. Potash feldspar was not observed, but may well occur in minor amounts. Only by the staining of sections, would its presence be unequivocable.

Biotite is ubiquitously apparent in amounts ranging from 4.0 to 26.4 per cent. It occurs in two habits in three out of five schists studied in detail, particularly in 1-63 and 2-63. Biotite in these instances occurs as somewhat ragged, well aligned slender flakes interdigitating with muscovite, and as generally larger flakes in "shadow zones" about garnet porphyroblasts, imparting an augen-like appearance to the garnet. Biotites of both varieties are markedly pleochroic, being in both cases orange brown with subtle reddish and greenish tints in the schists 1-63 and 2-63. In the remainder of the schists studied, biotite is predominantly pleochroic red-brown, with the exception of 3-63 where pleochroism is greenish brown.

Muscovite is probably both primary and secondary in origin, and occurs as slender flakes and in knots of randomly oriented minute flakes (sericite). The larger flakes generally range in size from 0.3 - 0.6 mm., but occasional flakes develop up to 2 mm. in length. Secondary white mica is probably the result of retrograde alteration of porphyroblastic minerals, and is associated with chlorite and disseminated opaque minerals.

Chlorite is particularly abundant in the schist from the Ruth Formation, where the modal content is 8.5 and 19.9 per cent in 136a-64 and 145-64 respectively. Elsewhere it is trivial in amount or non-existent. Chlorite forms both as ragged flakes generally associated with strongly corroded biotite, and as mats of randomly arranged minute flakes in knots of undoubtedly retrograde porphyroblastic minerals. Flakes are generally pale green in colour and slightly pleochroic.

Opaque minerals are ubiquitously present, usually disseminated throughout. Occasional larger grains occur which are in general xenoblastic. These

rarely exceed 1.5 mm. in size. Opaque minerals are particularly abundant in the schist, 136a-64 (modal content of 2.6 per cent).

Idioblastic to xenoblastic apatite is a common, although very minor accessory. Tourmaline is present in most schists occurring as xenoblastic, strongly pleochroic, grains. Tourmaline is usually a vivid yellow, often faintly tinged with blue; however, one specimen contains a tourmaline deep blue-green in colour. Zircon, where present, is trivial in amount, and generally occurs as minute inclusions within biotite, often exhibiting marked pleochroic haloes.

Staurolite was observed only in one schist (145-64), where it is porphyroblastic in habit and variable in size. Although appearing idioblastic in many rocks in hand specimen, staurolite is strongly corroded in outline when examined under the microscope. Porphyroblasts are present up to 3.5 by 2.0 cm. in size, but generally are much smaller. They are typically golden yellow in colour, and weakly pleochroic. They exhibit retrograde alteration rims, consisting of an innermost zone of minute randomly arranged sericite flakes, followed by a relatively narrow zone of pale green, slender chlorite flakes in random orientation. An outer zone, not always well defined, composed of fine specks of opaque ores, is also discernable. Sericite and chlorite generally pervade along minute fractures within strongly corroded staurolite porphyroblasts. Retrograde alteration appears to be complete in many instances within this schist, and also within another schist (136a-64) collected from a locality further to the south in the same formation. Considering the degree of hornflesing of the matrix of these two rocks, the staurolite and alteration rims are remarkably undeformed.

Sillimanite was observed in only one schist, where it occurs as minute swirls

of hair-like fibres (fibrolite) apparently replacing biotite which in turn envelopes corroded garnet. Sillimanite fibres also invade quartz granules in the same vicinity. This schist is hornfelsed, and occurs directly abutting against the Grey Creek Stock.

TEXTURAL ASPECTS

With the exception of three cases, the amphibolites, both garnetiferous and non-garnetiferous, examined in detail are remarkably similar texturally, being well lineated, generally medium grained, and nematoblastic. Of the three exceptions, two (4-63 and 65-64) are decidedly banded, consisting of thin amphibole-rich and felsic-rich interlayers. The third (180-64) exhibits a marked hornfelsed texture.

The schists are somewhat more variable in texture. Specimens 1-63 and 2-63 are typically well lineated rocks with a pronounced schistosity imparted by approximate interlayers of micas and quartz. Specimens 31a-63, 136a-64 and 145-64 contain a typical hornfelsed matrix. Retrograde textures are portrayed by porphyroblastic minerals in the latter two schists as mentioned above, while up-grading resulting from contact metamorphism, is well illustrated in 31a-63.

CHEMICAL ASPECTS OF AMPHIBOLITES, SCHISTS, AND ACID VEINS

Partial chemical analyses of twenty-five whole rocks were undertaken, eighteen of which were amphibolites, five schists, and two acid veins. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, and K_2O determinations were made in all cases, together with further analyses of "combined" H_2O and P_2O_5 for specimen 28c-63.

SAMPLE PREPARATION

All specimens used for whole rock chemical determinations were first cleaned of oxidised or soiled portions using a diamond saw, and then reduced using a "jaw crusher". After quartering to obtain a small aliquot of each specimen, these were pulverised by the use of a tungsten carbide lined "swing-mill" (Bleuler model).

ANALYTICAL PROCEDURES ADOPTED

With the exception of the determinations of FeO, Na_2O, and K_2O, and the complete analysis of specimen 28c-63, all remaining elements were determined by the X-ray fluorescence analytical technique. Procedures adopted for tablet making, standards used, complete recording conditions for X-ray fluorescence analyses, and calibration curves used, are to be found in Appendix A.

The garnet-bearing amphibolite (28c-63) was completely analysed by standard wet chemical procedures (Groves, 1951; Baadsgaard, 1960). Na_2O and K_2O determinations were made flame-photometrically, using a standard Perkin-Elmer instrument. FeO determinations were made using the Rowledge method modified by Groves (1951, p. 184) - see Chapter IV, p. 85, and Appendix B, for a discussion of this method.

All bulk rock chemical analytical results are recorded in Tables 2 and 4.

RELIABILITY OF RESULTS

Statistical data for the reliability of the seven oxides determined by X-ray fluorescence techniques, is presented in Table 22 of Appendix A. Of these

results, probably three are subject to notable error; these are SiO_2, Al_2O_3, and MgO. Spurious values may be encountered for Al_2O_3 and SiO_2, resulting from the absorption of Si secondary radiation by Al. This effect will be particularly prominent in the case of the schists, and may partly account for the high totals encountered.

Mass absorption effects, due to chemical and mineralogical differences existing between standard and unknown, should be minimised by careful choice of standards, which are chemically and mineralogically similar to the rocks being analysed. It is noteworthy that good standards were available to the writer for the amphibolites, whereas those for schists were not. High totals may result in the case of the schists, from the accumulative incremental error in each determination arising from the difference in the mass absorption coefficients of the unknown and the chemical standards used.

The determination of MgO is the lowest limit for chemical analyses using the X-ray fluorescence technique. Secondary radiation emitted by Mg is of such a low energy, that detectability is always a problem. The corresponding large conversion factor (wt.%/c.p.s.), resulting from the low counting rate, has an exaggerating effect on any fluctuations in the running conditions. If these conditions are not sufficiently stable, spurious values of MgO will undoubtedly be obtained.

Of the wet chemical determinations, probably only the FeO values (and consequently Fe_2O_3 values) are subject to any significant error. Errors in the FeO results are most likely sporadic, and probably on the low side. Further discussion of this is made in Chapter IV, p.85, and Appendix B.

Table 2. Partial bulk rock chemical analyses of Kootenay Lake amphibolites

	I. Garnet bearing amphibolites													II. Non-garnet bearing amphibolites				
	12–63	25a-63	28c-63 *	5-64	35-64	65-64	77-64	86-64	92-64	94-64	109-64	119-64	167-64	28h-63	4-64	38-64	171-64	180-64
SiO_2	49·55	47·47	50·93	46·46	46·64	49·13	38·66	48·95	48·61	48·77	48·80	48·85	50·64	47·55	50·36	50·56	49·45	50·64
TiO_2	3·13	1·52	1·49	1·87	1·85	3·81	2·46	2·53	2·41	1·51	2·06	2·31	1·93	1·41	1·28	2·15	1·59	3·57
Al_2O_3	12·47	13·61	15·32	13·57	13·79	13·98	13·89	13·14	12·88	13·92	13·83	13·38	14·02	16·38	14·56	12·32	14·33	12·71
Fe_2O_3	1·44	1·85	1·32	1·60	1·75	2·02	2·61	1·38	3·33	3·32	2·24	3·07	2·28	0·75	1·98	2·71	2·76	2·99
** FeO	12·09	10·76	10·23	11·28	10·93	11·29	10·69	11·43	10·17	9·22	10·39	10·04	10·04	10·18	9·78	11·91	9·61	11·73
MnO	0·21	0·22	0·23	0·21	0·23	0·19	0·25	0·20	0·22	0·21	0·20	0·21	0·20	0·18	0·20	0·21	0·21	0·22
MgO	5·18	6·72	7·05	6·17	6·50	5·40	7·49	6·28	5·84	6·83	6·17	6·06	6·72	7·82	7·27	4·74	7·05	4·74
CaO	10·61	11·56	10·21	11·21	11·29	10·58	13·21	11·27	10·45	11·60	11·14	10·81	11·03	12·07	11·54	9·48	11·16	9·51
** Na_2O	1·73	1·92	0·78	2·33	2·20	2·08	1·51	1·40	2·13	2·03	2·02	1·69	0·96	1·06	1·27	1·86	1·89	1·31
** K_2O	0·87	0·72	0·96	0·69	0·75	0·22	0·46	0·57	0·74	0·57	0·37	0·91	0·60	1·04	0·94	1·11	0·65	0·76
P_2O_5	---	---	0·19	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
H_2O^+	---	---	1·40	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
H_2O^-	---	---	0·04	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
TOTAL	97·28	96·35	100·15	95·39	95·93	98·70	91·23	97·15	96·78	97·98	97·22	97·33	98·42	98·44	99·18	97·05	98·70	98·18

Analyst: C. J. Dodds.

* Analysis of 28c – 63 determined completely by wet chemical methods

** Determined by wet chemical means

Table 3. Modal analyses based on two thousand points, of Kootenay Lake amphibolites.

I. GARNETIFEROUS AMPHIBOLITES

	12-63	25a-63	28c-63	5-64	35-64	65-64	77-64	86-64	92-64	94-64	109-64	119-64	167-64
QUARTZ	9·8	10·4	9·5	11·2	8·1	7·8	0·5	5·7	7·3	5·3	5·6	6·4	12·7
PLAGIOCLASE	10·0	9·7	12·8	11·7	16·1	13·5	7·0	12·0	15·8	15·7	15·8	17·0	12·6
K-FELDSPAR	—	—	—	—	—	—	—	—	—	—	—	—	—
HORNBLENDE	57·2	66·1	55·10	69·2	60·8	62·6	75·0	70·1	65·6	72·7	63·4	70·2	61·6
GARNET	13·3	6·6	10·7	3·4	8·4	* 1·0	11·2	3·9	5·1	3·0	8·1	1·8	7·3
BIOTITE	0·5	1·8	6·2	Tr.	1·9	—	0·2	0·8	0·8	Tr.	—	0·1	1·9
OPAQUE MINERALS	1·7	0·7	1·7	0·8	0·4	3·4	0·6	0·9	1·8	0·3	0·7	0·6	0·8
SPHENE	5·5	2·9	2·1	2·7	3·4	6·0	3·1	4·6	1·8	2·4	2·8	3·1	1·3
APATITE	1·3	0·9	0·7	0·5	0·5	1·3	0·1	0·5	0·7	0·3	0·5	0·4	0·5
EPIDOTE	0·3	0·3	—	—	Tr	0·2	0·3	0·2	0·1	0·2	0·2	0·2	0·1
SERICITE	0·4	0·4	1·2	0·5	0·4	3·2	1·5	1·0	0·9	0·1	1·2	0·2	0·9
CHLORITE	—	Tr	—	—	—	—	0·1	0·2	—	—	0·3	Tr	0·3
CALCITE	—	0·2	—	—	—	1·0	0·4	0·1	0·1	—	1·4	—	—
TOURMALINE	—	—	Tr	—	—	Tr	Tr	—	—	Tr	Tr	—	—
TOTAL	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0
PLAGIOCLASE COMPOSITION	An 34	An 40	An 54	An 38	An 36	An 41	An 46	An 54	An 46	An 47	An 38	An 45	An 60

II. NON-GARNETIFEROUS AMPHIBOLITES

	28h-64	4-64	38-64	171-64	180-64
QUARTZ	8·4	6·4	11·8	5·3	13·5
PLAGIOCLASE	19·0	19·2	17·2	17·0	17·0
K-FELDSPAR	—	—	—	—	—
HORNBLENDE	67·1	70·8	63·1	72·4	61·6
GARNET	—	—	—	—	—
BIOTITE	3·0	0·7	4·1	—	0·2
OPAQUE MINERALS	0·2	0·2	1·3	0·1	5·8
SPHENE	1·7	1·7	1·2	2·8	—
APATITE	0·2	0·5	0·6	0·5	1·0
EPIDOTE	—	0·2	0·4	0·2	0·1
SERICITE	0·4	0·3	0·3	1·7	0·8
CHLORITE	—	—	—	—	—
CALCITE	—	—	—	—	—
TOURMALINE	—	—	—	—	—
TOTAL	100·0	100·0	100·0	100·0	100·0
PLAGIOCLASE COMPOSITION	An 64	An 57	An 41	An 46	An 58

* Estimated from hand specimen.

Table 4. Partial bulk rock chemical analyses of garnetiferous schists, and garnet bearing acid igneous veins

I Garnetiferous schists

	1-63	2-63	136a-64	145-64	152-64
SiO_2	61.50	65.11	60.96	82.59	80.29
TiO_2	1.01	1.02	.95	.69	.49
Al_2O_3	19.52	19.37	18.40	10.93	12.61
Fe_2O_3	2.20	2.89	3.25	2.12	1.57
FeO*	5.63	4.87	5.40	3.54	3.32
MnO	.04	.04	.07	.06	.06
MgO	1.64	1.42	3.07	1.53	1.86
CaO	.48	.49	1.25	.72	.53
Na_2O*	.77	.51	1.98	1.55	1.69
K_2O*	6.18	5.59	2.86	1.44	2.71
Total	98.97	101.31	98.19	105.17	105.13

II Garnet-bearing acid veins

	5-63	22-63
SiO_2	74.51	75.02
TiO_2	.01	.02
Al_2O_3	14.29	14.07
Fe_2O_3	.09	.09
FeO*	.55	.81
MnO	.08	.25
MgO	.10	.10
CaO	.99	1.18
Na_2O*	6.33	4.62
K_2O*	3.52	4.16
Total	100.47	100.32

Analyst: C. J. Dodds

* Determined by wet chemical methods; remainder of analyses by X-ray fluorescence

Table 5. Modal analyses (based on two thousand points) of garnetiferous schists

	1-63	2-63	136a-64	145-64	152-64
Quartz	53.0	30.3	28.0	58.9	71.0
Plagioclase	.9	1.1	10.3	2.8	4.8
K Feldspar	-.-	-.-	-.-	-.-	-.-
Garnet	* 2.0	*15.0	1.2	3.1	.5
Staurolite	-.-	-.-	-.-	* 2.0	-.-
Biotite	26.4	15.2	4.2	4.0	11.0
Muscovite	16.7	37.2	32.6	18.1	11.4
Chlorite	-.-	Tr	19.9	8.5	-.-
Opaque Minerals	.7	.7	2.6	1.7	1.0
Apatite	.2	.2	.4	.5	.2
Tourmaline	.1	.3	.8	.4	.1
Zircon	Tr	Tr	-.-	-.-	-.-
Total	100.0	100.0	100.0	100.0	100.0
Plagioclase Composition	An 38	?	An 41	An 28	An 26

* Estimated from hand specimen

DISCUSSION OF RESULTS

GRADE OF METAMORPHISM

A knowledge of the exact grade of metamorphism is of obvious paramount importance, if any variations in garnet composition (especially within the amphibolites) are to be related to grade changes alone.

Crosby (1960), adopting the scheme of Barrow (1912), has erected isograds within the central Kootenay Lake area, based on the first appearance of the index minerals biotite, staurolite, kyanite, and sillimanite. It is to be noted that the isograd sequence is disrupted somewhat, by the later normal Nasookin and Crawford Bay faulting (see Fig. 5, p.27), within the Crawford Peninsula and Bay areas. From the position of these isograds, it would appear that with the exception of 65-64, and probably 4-64 and 5-64, all the amphibolites studied in detail were at least middle to upper almandine-amphibolite facies* grade. According to Crosby's isograd mapping, the remaining amphibolites would appear to be at least upper greenschist facies. Of the garnet mica schists examined by the writer, four (viz. 1-63, 2-63, 3-63 and 31a-63) appear to be within the sillimanite zone (ie. middle to upper almandine-amphibolite facies), one (152-64) in the kyanite zone (lower middle almandine amphibolite), two (136-64 and 145-64) in the staurolite zone (lower almandine-amphibolite), and one (57-64) in the garnet zone (uppermost greenschist).

Corroboration of these grades, determined by Crosby, is a difficult matter, especially in the case of the amphibolites. Although specimens were collected and thin sections made of the metasedimentary rocks directly enveloping the

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*N.B. Usage of metamorphic facies is strictly after Turner and Verhoogen (1960).

amphibolites, little was gleaned in the way of grade indicators. Of the garnet mica schists examined in detail, only two contained diagnostic mineral assemblages (viz. 31a-63 and 145-64).

Unfortunately, basic assemblages are by no means as reliable or precise as pelitic assemblages for use as indicators of metamorphic grade. The erection of the various facies, and subfacies of progressive regional metamorphism, rely heavily upon the mineralogical changes inherent in pelitic assemblages. In fact, most facies schemes use these mineralogical changes as a basic framework. This clearly shows the relative inadequacies of this system of classification, especially in basic assemblages within the middle grades of regional metamorphism. The P.T. stability field of hornblende covers a wide range, from the upper greenschist to the lower part of the granulite facies. Hornblende usually forms the most abundant mineral in amphibolites (together with plagioclase, often the sole constituents). In view of the great flexibility to diadochic substitution permitted by the amphibole structure, gross mineralogical changes are not available to the petrographer over a wide range of grade change within basic assemblages.

Several intensive studies have been made on the mineralogical, textural, and chemical changes resulting from progressive regional metamorphism of basic rocks. Important contributions were made by Wiseman (1934), Miyashiro (1958), and Engel and Engel (1962a, 1962b and 1964). These workers observed certain rather illuminating changes, amongst which are the progressive increase in the An content of plagioclases, changes in the Z axial colour and to some degree the composition of hornblende, and changes in the $Fe^{+3}/(Fe^{+3} + Fe^{+2})$ and $Fe^{+2}/(Fe^{+2} + Mg^{+2})$ ratios.

An attempt has been made by the writer to tabulate these changes noted in basic assemblages with progressive increase in metamorphic grade. These are recorded in Table 6. Although this table shows the obvious limitations of this scheme toward the exact "pin-pointing" of metamorphic grade in basic assemblages (witness the overlapping of the ranges of the various "indicators" used), trends with progressive regional metamorphism, at least, become apparent.

Assemblages for all rocks studied in detail by the writer, are to be found in Table 7. Plagioclase composition ranges between sodic andesine and calcic labradorite, while Z axial colours in hornblende (although typically brown-green) vary from dark-bluish-green to red-brown. There appears to be, however, no systematic agreement between these two features (as indicated in Table 6), which might be diagnostic of trends or grade of metamorphism.

$Fe^{+3}/(Fe^{+3} + Fe^{+2})$ and $Fe^{+2}/(Fe^{+2} + Mg^{+2})$ ratios for all amphibolites studied by the writer are presented in Table 8. There is remarkably little variation in both sets of values for these ratios. Although these ratios, when compared with Miyashiro's values, are not entirely convincing in their indication of metamorphic grade, they do not, on the other hand, contradict the grade of metamorphism implied by the position of Crosby's isograds.

In the basic assemblages examined, several interesting features are presented by certain minerals. Sphene in all but one case (180-64), is ubiquitously present, and generally associated with the opaques (enveloping these in many cases, in the form of rims). Engel and Engel (1962) have noted the disappearance of sphene south of Emeryville, and have correlated this with the disappearance of muscovite within the enclosing paragneiss. Presumably this change is between the two

Table 6. A tabulation of the changes observed in basic assemblages, with progressive regional metamorphism.

TURNER AND VERHOOGEN (1960) FACIES CLASSIFICATION OF REGIONAL METAMORPHIC ROCKS		CHANGES OBSERVED IN BASIC ASSEMBLAGE WITH GRADE CHANGE									
		PLAGIOCLASE CONTENT				Z AXIAL COLOUR OF HORNBLENDE			AMPHIBOLITE RABOS (Miyashiro)		CHEMICAL VARIATION
		TURNER and VERHOOGEN	WISEMAN (1934)	MIYASHIRO (1958)	ENGEL (1962a)	WISEMAN (1934)	MIYASHIRO (1958)	ENGEL (1962a)	$Fe^{+3}/(Fe^{+2}+Fe^{+3})$	$Fe^{+2}/(Mg^{+2}+Fe^{+2})$	ENGEL (1962b)
GREEN SCHIST FACIES	CHLORITE ZONE Qtz.-ab-musc-chl (sub facies)	Albite		Albite to sadic aligoclase (An $_{7-15}$)	These grades not present in Engel and Engel NW Adirondack Mts. study.	Actinolite	Actinalite (pale green ta colarless) (law in Al and alkalies)	These grades not present	0·29, 0·27 0·26, 0·22	0·21, 0·40 0·29, 0·28	These grades not present
	BIOTITE ZONE Qtz -ab.-ep.-gnt. (sub facies)	Albite									
	GARNET ZONE Qtz.-ab.-ep.-gnt. (sub facies)	Albite AnO-7	Albite(An $_5$) Andesine(?)	Ep-amphibalite Facies absent Oligoclase		Blue-green hbl. + act.	Ep.-amphibolite Facies absent		Ep.-amphibalite Facies absent	Ep-amphibalite Facies absent	
ALMANDINE-AMPHIBOLITE FACIES	STAUROLITE ZONE Staur.-alm.-musc. (sub facies)	An $_{15-30}$		(An $_{20-30}$) alig (An $_{30}$)		Blue green hornblende	Blue green hornblende		0·23, 0·14 0·13	0·46, 0·36 0·40	
	KYANITE ZONE Ky-alm.-musc. (sub facies)		Andesine ta sadic lab.	ta lab. (An $_{65}$)			deeper bluish green in Al and alk.				
	SILLIMANITE ZONE Sill.-alm.-musc. (sub facies)	(?)	(?)	and. (An $_{50}$)	(?) and.			(?)	0·23 0·16, 0·02	0·31 0·56, 0·51	(?) increase in Ca, Mg, (?) Al decrease in Si, K_2O, H_2O, F, Cl, Fe^{+2}
	SILLIMANITE ZONE Sill.-alm.-ar (sub facies)			ta byt. (An $_{85}$)	ta	greenish brown	greenish ar yellowish brown	greenish brawn ta			
GRANULITE FACIES	HORNBLENDE GRANULITE (sub facies)			(?)	sad. lab (?)	brown (?)	brown (?)	brawn (?)	(?)	(?)	
	PYROXENE GRANULITE (sub facies)										

Table 7. Basic and pelitic mineral assemblages of the rocks studied from the central Kootenay Lake area

BASIC

	ASSEMBLAGES
4-63	gnt-pl(calc.and.)-hbl(dark-bluish-green) -qtz -(bt).
12-63	gnt-pl(sod. and.)-hbl(red-brown) -qtz-(ep)-(bt).
25a63	gnt-pl(and.)-hbl(brown) -qtz-(ep)-(bt).
28c63	gnt-pl(sod. lab.)-hbl(green-brown) -qtz - bt .
29a63	gnt-pl(calc.and.)-hbl(brown-green) -qtz-(ep)-(bt).
5-64	gnt-pl(sod. and.)-hbl(dark-brown-green) -qtz .
35-64	gnt-pl(sod. and.)-hbl(dark-brown-green) -qtz-(ep)- bt .
65-64	gnt-pl(calc.and.)-hbl(yellow-brown-green) -qtz-(ep) .
77-64	gnt-pl(calc.and.)-hbl(dark-brown-green) -qtz-(ep)-(bt).
86-64	gnt-pl(sod. lab.)-hbl(yellow-green) -qtz-(ep)- bt .
92-64	gnt-pl(calc.and.)-hbl(dark-brownish-green) -qtz-(ep)- bt .
94-64	gnt-pl(calc.and.)-hbl(dark-green) -qtz-(ep)-(bt).
109-64	gnt-pl(sod. and.)-hbl(yellow-green) -qtz-(ep) .
119-64	gnt-pl(calc.and.)-hbl(dark-brownish-green) -qtz-(ep)-(bt).
167-64	gnt-pl(lab.)-hbl(yellow-greenish-brown)-qtz-(ep)- bt .
28h63	pl(calc.lab.)-hbl(greenish-brown) -qtz - bt .
4-64	pl(sod. lab.)-hbl(dark-brownish-green) -qtz-(ep)- bt .
38-64	pl(calc.and.)-hbl(dark-bluish-green) -qtz-(ep)- bt .
171-64	pl(calc.and.)-hbl(deep-bluish-green) -qtz-(ep) .
180-64	pl(sod. lab.)-hbl(yellow-brownish-green)-qtz-(ep)-(bt).

PELITIC

	ASSEMBLAGES
1-63	gnt -musc-bt -qtz-pl(sod. and.) .
2-63	gnt -musc-bt -qtz-pl(?) .
3-63	gnt -bt -qtz-pl(calc.and.) .
31a63	gnt-sill. -musc-bt -qtz .
57-64	gnt -musc-bt-(chl.)-qtz-pl(?) .
136a64	gnt -musc-bt-(chl.)-qtz-pl(calc.and.) .
145-64	gnt-staur.-musc-bt-(chl.)-qtz-pl(calc.olig.) .
152-64	gnt -musc-bt- -qtz-pl(calc.olig.) .

Table 8

$Fe^{+3}/(Fe^{+3} + Fe^{+2})$ ratios for Kootenay Lake amphibolites:

12-63	25a-63	28c-63	5-64	35-64	65-64	77-64	86-64	92-64
0.10	0.13	0.10	0.11	0.13	0.14	0.18	0.10	0.23
94-64	109-64	119-64	167-64	28h-63	4-64	38-64	171-64	180-64
0.24	0.16	0.22	0.17	0.06	0.15	0.17	0.21	0.19

$Fe^{+2}/(Fe^{+2} + Mg^{+2})$ ratios for Kootenay Lake amphibolites:

12-63	25a-63	28c-63	5-64	35-64	65-64	77-65	86-64	92-64
0.57	0.47	0.45	0.51	0.49	0.54	0.45	0.51	0.49
94-64	109-64	119-64	167-64	28h-63	4-64	38-64	171-64	180-64
0.43	0.49	0.48	0.47	0.42	0.43	0.59	0.43	0.58

sillimanite sub-facies of Turner and Verhoogen, and may well suggest that the amphibolites examined by the writer are, with the exception of 180-64, at least no higher than the sillimanite-almandine-muscovite sub-facies. The case of 180-64 is probably more complicated, since this amphibolite has been pronouncedly affected (hornfelsed) by the intrusion of the Bayonne Batholith.

Biotite is notably present in most amphibolites studied by the writer. As has been suggested by Miyashiro (1958, p. 237), three possibilities may be considered regarding the origin of biotite in amphibolites:

" (1) Isochemical metamorphism of some K-rich igneous material

(2) Isochemical metamorphism of basic materials mixed with some sediments

(3) Metamorphism accompanied by material transfusion (especially K and Si)".

The writer tends to favour the latter possibility (with some slight modifications) for the origin of the biotites developing in the Kootenay Lake amphibolites. Petrographic and field evidence appears to indicate a "secondary" formation of biotite on the following grounds:

(1) Biotite seems to be more prominent when the enclosing metasedimentary rocks and occasionally the amphibolites themselves, are markedly pervaded by acid igneous material. This fact was also observed by Crosby (p. 70) within the Kootenay Lake area. Engel and Engel (1962a, p. 56), note that "red-brown biotite is a common accessory mineral, especially in the amphibolites that have been deformed or injected by granite or pegmatite".

(2) Petrographic evidence indicates that there is generally randomness in orientation of the biotite flakes (ie. opposed to the well developed

lineation of the hornblendes).

(3) Biotite appears to replace hornblende in certain cases, and to be associated with the breakdown of garnet. Further discussion concerning this latter observation is given in a later section.

The writer feels that the origin of the biotite is partly the result of potash metasomatism occurring at a later stage than the development of the garnet porphyroblasts and hornblende, and conceivably coincident with the injection of acid igneous material.

In most of the amphibolites examined by the writer, epidote is present as a trivial to minor accessory. It occurs as minute, pale yellow to colourless granules generally included within plagioclase. Crosby has also mentioned the occurrence of epidote in this rock type within the central Kootenay Lake area.

Epidote, according to Turner and Verhoogen (1960), is in general present only in basic assemblages up to the kyanite zone. A similar conclusion is also pointed out by Miyashiro (1958, p. 264). No mention is made by Engel and Engel (1962a) of the presence of epidote in the amphibolites of the Northwest Adirondack Mountains.

The diminution in the amount of epidote with increased metamorphic grade is probably associated in part with the increase in An content of plagioclase, as has been pointed out by several workers (Wiseman, 1934, p. 385; Ramberg, 1952, p. 50; Miyashiro, 1958, p. 247). The presence of this mineral in the Kootenay Lake amphibolites within the sillimanite zone, is considered by Crosby to be due to the "maintainance of the activity of H_2O at some minimal level during the metamorphic crystallisation". This explanation may well be true, since as Crosby

points out, "the activity of H_2O is an important controlling factor in the formation of epidote".

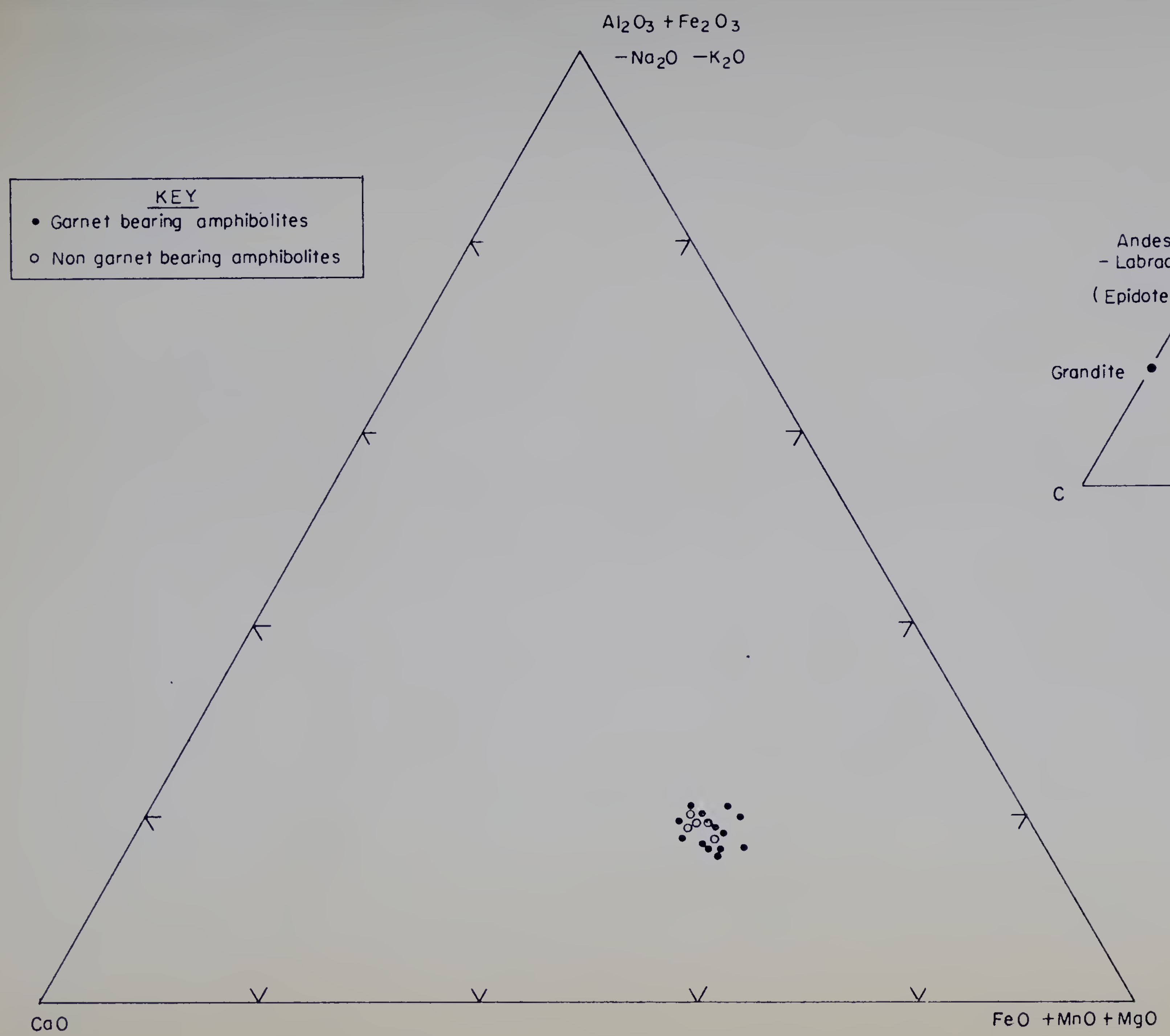
In summary, the writer finds neither evidence which fully corroborates nor evidence which refutes Crosby's zones of metamorphism. It must therefore tentatively be concluded, from the limited evidence presented of the changes observed in basic assemblages, that the degree of metamorphism varies very little within the amphibolites examined by the writer. Any variation in grade probably lies within the almandine-amphibolite facies of Turner and Verhoogen, from the lower middle to possibly the uppermost part of this facies. The writer finds no concrete evidence to signify that any of the amphibolites examined are as low a grade as greenschist (garnet zone), as is suggested by the location of certain amphibolites in reference to Crosby's isograds. Only two of the garnet mica schists studied show minerals diagnostic of grade, and these are in agreement with the zones of Crosby.

ACF AND AKF DIAGRAMS

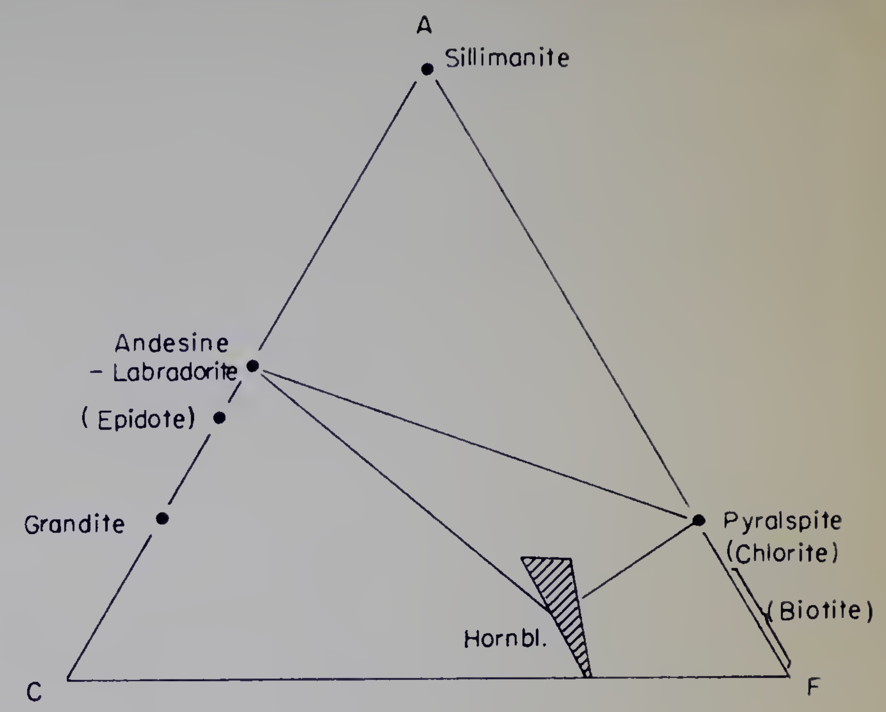
Chemical analyses of all amphibolites studied have been plotted on an ACF diagram, Fig. 6, and those from all schists on both AKF and ACF diagrams, Figs. 7 and 8 respectively. Eskola's (1939) "rules" of construction were used in plotting these diagrams.

Fig. 6 indicates the remarkable similarity in the chemistry of both garnet-bearing and non-garnetiferous amphibolites. There is a definite lack in grouping of the analyses in the AKF diagram for the schists. The two schists (1-63 and 2-63) collected from the vicinity of the Grey Creek Stock are notably higher in

Figure 6. ACF diagram for analysed Kootenay Lake amphibolites; (inset) typical Kootenay Lake basic assemblage.



ACF DIAGRAM FOR ANALYSED KOOTENAY LAKE AMPHIBOLITES



Typical Kootenay Lake basic assemblage

Figure 6

Figure 7. AKF diagram for analysed Kootenay Lake schists; (inset) typical assemblage from Kootenay Lake schists.

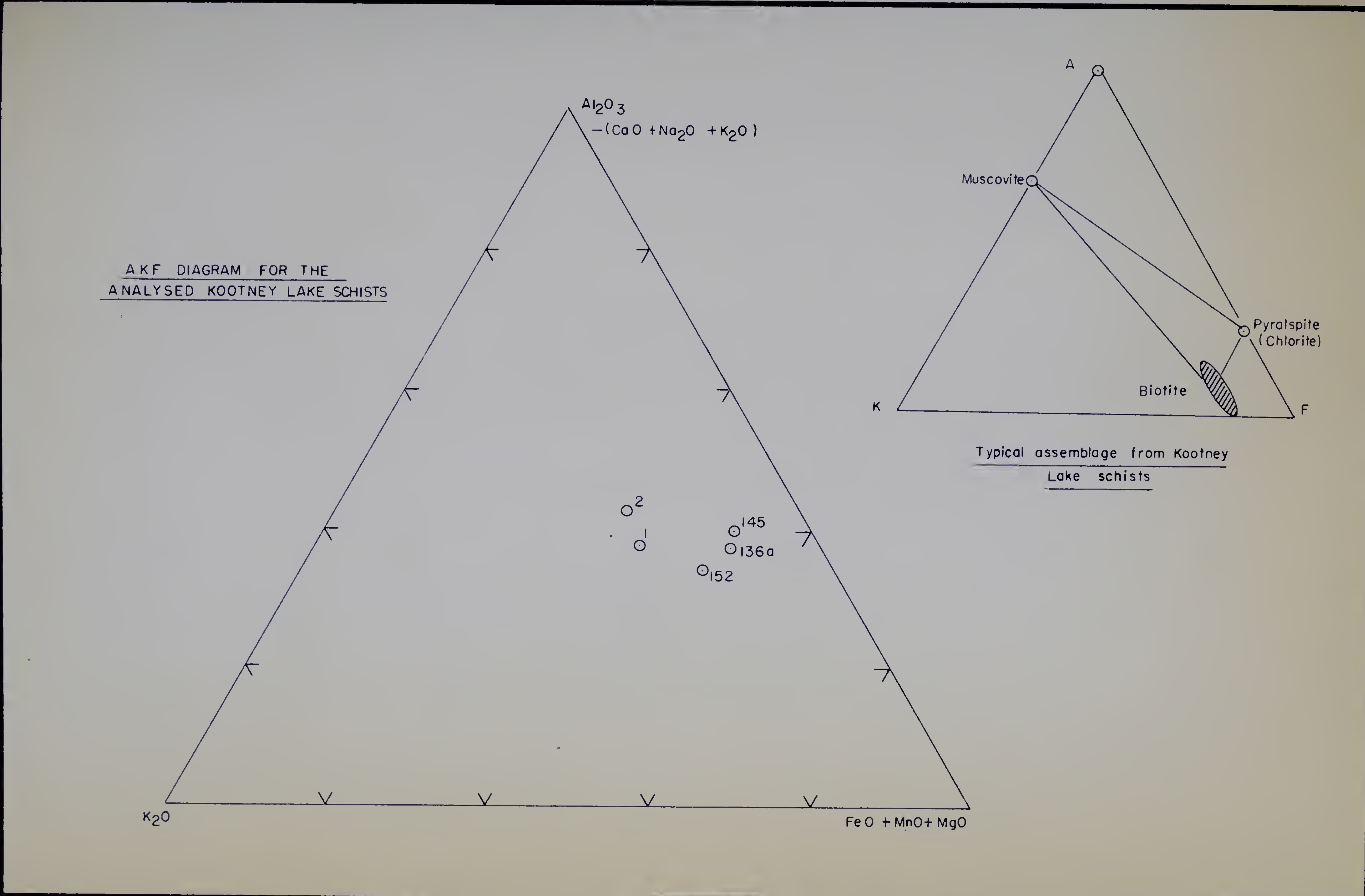

AKF DIAGRAM FOR THE
ANALYSED KOOTNEY LAKE SCHISTS
Al_2O_3
$-(CaO + Na_2O + K_2O)$
2
1
145
136a
152
K_2O
$FeO + MnO + MgO$
A
Muscovite
Pyralspite
(Chlorite)
Biotite
K
F
Typical assemblage from Kootney
Lake schists

Figure 7.

Figure 8. ACF diagram for the analysed Kootenay Lake schists; (inset) five-fold chemical classification of metamorphic rocks (after Turner and Verhoogen, 1958).

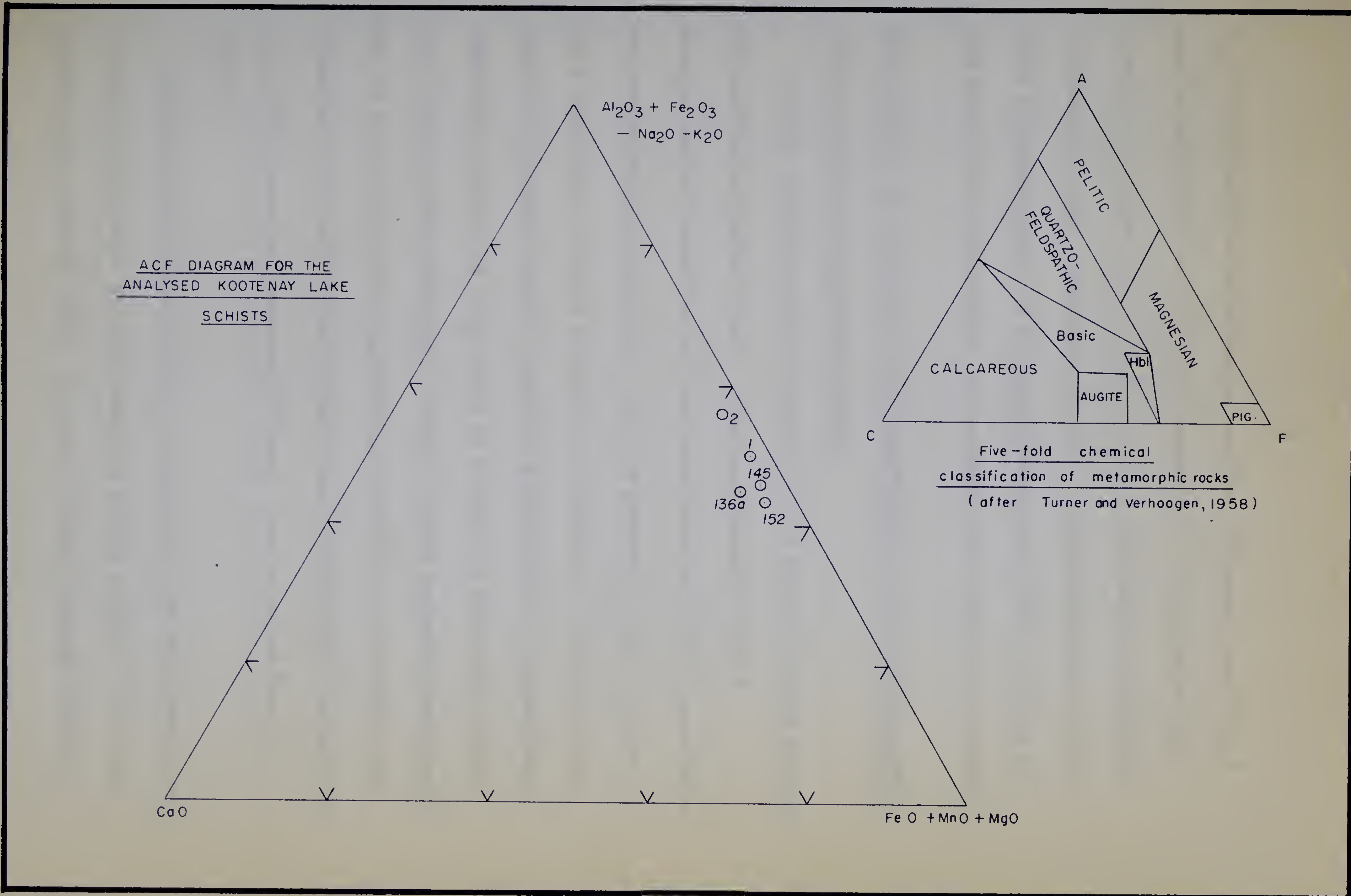

ACF DIAGRAM FOR THE
ANALYSED KOOTENAY LAKE
SCHISTS
$Al_2O_3 + Fe_2O_3$
$- Na_2O - K_2O$
CaO
FeO + MnO + MgO
2
1
145
136a
152
A
C
F
PELITIC
QUARTZO-
FELDSPATHIC
MAGNESIAN
Basic
CALCAREOUS
Hbl
AUGITE
PIG.
Five-fold chemical
classification of metamorphic rocks
(after Turner and Verhoogen, 1958)

Figure 8.

K_2O than the schists collected from the west side of Kootenay Lake. Fig. 8 shows the ACF plot for the schists. The composition fields adopted by Fyfe, Turner and Verhoogen (1958, p. 200) for the five-fold chemical classification of metamorphic rocks, is included as an inset, for comparison purposes. The schists fall approximately into the pelitic compositional field, but in view of their generally high modal quartz, may probably be best regarded as semipelites.

COMPARISON OF KOOTENAY LAKE AMPHIBOLITES WITH OTHER MAFIC ROCKS (IGNEOUS AND METAMORPHIC)

C.I.P.W. norms have been calculated for all but one of the central Kootenay Lake amphibolites studied in detail. These are presented in Table 9. Average chemical compositions and norms were determined for both garnetiferous and non-garnetiferous amphibolites. These are presented in Table 9, column 1 and 2 respectively. It should be noted that the analysis of 77-64 was not considered in the average chemical composition determination of the garnetiferous amphibolites, because the SiO_2 content for this rock was substantially different (lower) from the other amphibolites. Average chemical composition and norms of both the garnetiferous and non-garnetiferous amphibolites are remarkably alike. Comparison is then made of these average values, in terms of other average mafic rocks of both igneous and metamorphic kindred. These values are shown in Table 10.

Probably the most striking similarity in composition of the basic igneous rocks is portrayed by the normal tholeiitic basalt and dolerite (column 7). The values are mainly after Nockolds (1954). The olivine tholeiite, although relatively

Table 9. C.I.P.W. norms for Kootenay Lake amphibolites

I Garnet-bearing amphibolites

	12-63	25a-63	28c-63	5-64	35-64	65-64	86-64	92-64	94-64	109-64	119-64	167-64
Quartz	4.7	-.-	6.8	-.-	-.-	4.8	3.8	2.5	.8	1.9	3.6	7.9
Orthoclase	5.0	4.5	5.6	3.9	4.5	1.1	3.3	4.5	3.3	2.2	5.6	3.3
Albite	14.7	16.3	6.8	19.9	18.9	17.8	12.1	17.8	17.3	17.3	14.2	7.9
Anorthite	23.6	26.4	35.0	24.5	25.3	28.1	27.8	23.4	27.2	27.5	26.1	32.5
Diopside	23.6	25.2	12.3	25.4	25.0	20.0	22.9	23.2	24.7	22.7	22.5	18.2
Hypersthene	16.3	12.5	26.6	4.4	6.8	16.1	19.5	16.0	16.8	17.9	16.2	21.3
Olivine	--.-	5.7	--.-	11.0	8.4	--.-	--.-	--.-	--.-	--.-	--.-	--.-
Magnetite	2.1	2.8	1.9	2.3	2.6	3.0	2.1	4.9	4.9	3.2	4.4	3.3
Ilmanite	5.9	2.9	2.9	3.5	3.5	7.3	4.9	4.6	2.9	4.0	4.4	3.7
Apatite	-.-	-.-	.3	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-

II Non garnet-bearing amphibolites

	28h-63	4-64	38-64	171-64	180-64
Quartz	-.-	2.6	5.9	1.1	10.9
Orthoclase	6.1	5.6	6.7	3.9	4.5
Albite	8.9	11.0	15.7	16.2	11.0
Anorthite	37.0	31.1	22.0	28.6	26.7
Diopside	18.6	21.3	20.4	21.8	16.8
Hypersthene	14.8	21.9	17.0	19.9	16.5
Olivine	8.4	--.-	--.-	--.-	--.-
Magnetite	1.2	2.8	3.9	3.9	4.4
Ilmanite	2.7	2.4	4.1	3.0	6.8
Apatite	-.-	-.-	-.-	-.-	-.-

Table 10. Average chemical compositions and norms of Kootenay Lake amphibolites, basic igneous rocks (Nockolds), amphibolite from the Adirondack Mts., the Abukuma plateau, and amphibolites (Poldervaart).

	Average Kootenay Lake amphibolites and basic igneous rocks										Amphibolites				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	48.73	49.71	51.51	46.65	48.36	50.28	50.83	47.90	45.78	46.77	48.20	47.89	47.23	48.13	50.3
TiO_2	2.20	2.00	.84	3.12	1.32	.89	2.03	1.65	2.63	3.00	1.89	1.56	1.67	2.00	1.6
Al_2O_3	13.66	14.06	13.95	15.52	16.84	17.67	14.07	11.84	14.64	14.65	14.45	14.63	15.87	17.28	15.7
Fe_2O_3	2.13	2.24	2.00	2.06	2.55	1.30	2.88	2.32	3.16	3.71	3.50	1.85	2.07	1.14	3.6
FeO	10.66	10.64	8.61	9.9	7.92	7.46	9.00	9.80	8.73	7.94	10.53	11.20	9.57	11.13	7.8
MnO	.21	.20	.22	.15	0.18	.14	.18	.15	.20	.15	.25	.25	.28	.28	.2
MgO	6.24	6.32	8.00	5.93	8.06	9.27	6.34	14.07	9.39	6.82	6.62	7.41	8.13	5.51	7.0
CaO	10.98	10.75	10.83	4.87	11.07	9.72	10.42	9.29	10.74	12.42	10.25	11.54	11.48	9.66	9.5
Na_2O	1.77	1.48	1.75	2.16	2.26	1.96	2.23	1.66	2.63	2.59	1.94	2.19	2.31	2.58	2.9
K_2O	.66	.90	.59	3.69	.56	.63	.82	.54	.95	1.07	.96	.58	.31	.74	1.1
P_2O_5	-.--	-.--	.09	.50	.24	.21	.23	.19	.39	.37	.18	.14	.14	.25	.3
H_2O^+	-.--	-.--	1.28	3.83	.64	.47	.91	.59	.76	.51	1.31	.72	1.69	1.65	-.-
No. of Analyses	12	5	4	4	160	39	137	28	96	22	?	?	3	2	200

C.I.P.W. norms

Quartz	2.2	3.5	3.6	-.-	-.-	-.-	3.7	-.-	-.-	-.-	.4	-.-	-.-	-.-
Orthoclase	3.9	5.6	3.3	21.7	3.3	3.9	5.0	3.3	5.6	6.1	5.7	3.5	1.8	4.4
Albite	15.2	12.6	14.7	18.4	18.9	16.8	18.9	14.1	19.5	21.0	16.4	18.5	19.6	21.8
Anorthite	27.2	28.9	28.6	21.7	34.2	37.3	25.9	23.3	25.7	25.3	27.9	28.4	32.0	33.4
Diopside	22.2	20.0	20.4	-.-	15.4	7.5	19.8	18.2	20.7	27.5	17.9	23.0	19.7	10.7
Hypersthene	18.5	20.1	23.0	13.1	14.2	27.6	17.2	18.8	-.-	-.-	21.4	8.5	4.3	14.6
Olivine	-.-	-.-	-.-	9.7	6.5	2.3	-.-	15.1	16.6	7.9	-.-	11.3	14.6	7.8
Magnetite	3.0	3.2	3.0	3.0	3.7	1.9	4.2	3.5	4.6	5.3	5.1	2.7	3.0	1.6
Ilmanite	4.3	3.8	1.7	5.7	.26	1.7	3.8	3.2	5.0	5.8	3.7	3.0	3.2	3.8
Apatite	-.-	-.-	.1	1.0	.7	.5	.5	.4	1.0	.9	.4	.3	.4	.6

1. Average composition of garnetiferous Kootenay Lake amphibolites.
2. Average composition of non-garnetiferous Kootenay Lake amphibolites.
3. Average composition of 4 Purcell sills (Hunt, 1961, p.97).
4. Average composition of 4 Purcell lavas (Hunt, 1961, p.97).
5. Composition of average gabbro (Nockolds, 1954, p.1020)
6. Composition of average norite (Nockolds, op cit.)
7. Average composition of normal tholeiitic basalt and dolerite (Nockolds, 1954, p. 1021).
8. Average composition of tholeiitic olivine basalt (Nockolds, op cit.).
9. Average composition of normal alkali basalt and dolerite (Nockolds, op. cit.).
10. Average composition of alkali basalt without olivine (Nockolds, op. cit.).
11. Average composition of Emeryville amphibolite (Engel and Engel, 1962a, p. 63).
12. Average Colton amphibolite (Engeland Engel , 1962a).

13, 14. Average composition of amphibolites from zones B and C respectively (Miyashiro, 1958).

15. Average composition of 200 amphibolites (water-free), (Poldervaart, 1955, p. 136).

similar, differs only in the expected lower SiO_2 and MgO contents. An interesting similarity exists between the few Purcell sill analyses available (Hunt, 1960, p. 97) - column 3, Table 10. Differences, however, exist in the SiO_2 (higher), and FeO and MgO (lower) contents of these rocks. The analyses of the lavas (column 4, Table 10) from the same area, are relatively variable in composition, and consequently present poorer comparisons. An average value taken for these analyses, shows the lavas to be notably higher in K_2O, H_2O and Al_2O_3 contents, and lower in CaO, when compared with the Kootenay Lake amphibolites.

A comparison with amphibolites from other areas is also made. A striking similarity is found to exist between the Kootenay Lake amphibolites and the amphibolites from the Adirondack Mountains, particularly in the Emeryville area (column 11, Table 10). The Colton amphibolites are somewhat more "basic" than those from the Kootenay Lake (column 12, Table 10). Engel and Engel (1962a), have made further comparison with amphibolites from other North American localities, and found strong chemical resemblance between these and the Adirondack amphibolites. Comparison is made of the Kootenay Lake amphibolites and those of the Gosaisyo-Takanuki area, Japan, from Miyashiro's Zones B and C (columns 13 and 14 respectively). These Japanese amphibolites are notably different in Al_2O_3, MnO, MgO, and CaO (all higher). Column 15, Table 10 was included for comparison between the Kootenay Lake and the average of 200 amphibolites (calculated on a water-free basis) after Poldervaart (1955). Unfortunately, "combined" H_2O was not determined by the writer, therefore, an exact comparison is not possible. However, it is felt that the

analyses of the Kootenay Lake amphibolites would compare with this average if H_2O^+ had been determined because Engel and Engels' values are in striking agreement with Poldervaart's average.

ORIGIN OF THE KOOTENAY LAKE AMPHIBOLITES

Three possibilities may be considered in regard to the origin of the Kootenay Lake amphibolites represented in this study. They are:

(1) metamorphosed basic igneous rocks - ie. ortho-amphibolites, including meta-dolerites, meta-basalts, or meta-basic tuffs.

(2) metamorphosed calcareous or dolomitic shales - ie. para-amphibolites.

(3) metasomatised calcareous layers of composition dissimilar to the amphibolites, or perhaps the product of metamorphic segregation.

Although Crosby (1960, p. 56) has postulated a metasomatic origin for certain thin amphibolite layers between carbonate beds in the Houghton Creek and Badshot Formations, he dismisses such an origin for the "massive bodies" of amphibolites occurring within these two formations, and in the McGregor Lake Formation. The latter includes those amphibolites considered in this study. The writer tends to agree with Crosby's postulation, since no textural or mineralogical evidence appears to be present to substantiate this. A metasomatic origin for the amphibolites is therefore tentatively dismissed. Metamorphic segregation as a mechanism in producing the examined amphibolites is also rejected on the basis of the sharp contacts exhibited by these bodies with the enveloping metasediments, and the lack of any evidence of transition zones having existed between the two.

The writer tends to favour the first of the two remaining possibilities for the

origin of the amphibolites studied, ie. that they are ortho-amphibolites. It is readily admitted, however, that no concrete evidence can be put forward which indisputably suggests either a sedimentary or an igneous origin for the Kootenay Lake amphibolites. A sedimentary origin may well be indicated by the fact that the amphibolite bodies, especially in the case of those in the Houghton Creek and McGregor Lake Formations, occur within a predominantly calcareous sequence. The writer feels that this is the only evidence that suggests such an origin for the amphibolites. Amphibolitic rock types, almost certainly sedimentary in origin, are fairly common within these sequences, bearing abundant diopside and biotite (also phlogopite) in addition to hornblende.

The evidence that the Kootenay Lake amphibolites are of igneous parentage, is also slim. No relict primary textures indicating that these rocks were once basic sills or flows, were observed by the writer or by Crosby. This could be explained by obliteration of these textures as a result of the intensity of metamorphism and deformation undergone by these rocks. The writer examined approximately one hundred amphibolites of rock type similar to those studied in detail, and all have sharp contacts with the enclosing metasediments. On the other hand, no fine grained margins were observed, which might indicate an igneous parentage.

Small amounts of biotite present within the amphibolites examined can probably be explained by metasomatic introduction of K_2O and need not be indicative of a sedimentary origin for these rock types. The fact that the amphibolite bodies are generally concordant with the foliation of the enveloping metasedimentary rocks, is by no means proof that they were originally basic

sedimentary rocks. It could equally well be argued that they were originally basic sills or volcanic flows. The two finely banded amphibolites (65-64 and 4-63), could either be of igneous (tuffs) or sedimentary parentage. In addition, the amphibolites studied in detail are an exceedingly chemically uniform series of rocks which compare well in composition with certain basic igneous rocks (particularly those of tholeiite basaltic type).

Basic intrusive and extrusive rocks abound in the Precambrian directly to the east and to the south east of the central Kootenay Lake area (described by Rice (1941), Reesor (1958), and by Hunt (1961) respectively). These rocks have been shown to be Precambrian in age by radiometric (K-Ar) determination (Hunt, 1961). The Kootenay Lake amphibolites, therefore, cannot be regarded as possible metamorphosed equivalents to these. However, the Kaslo volcanics, considered to be probably Triassic in age (fossil evidence), contain intrusive as well as extrusive members. These intrusive members are seen to invade the Milford and older rocks. It is possible that some amphibolites (in particular the massive amphibolite bodies) once represented rocks akin to these. In fact this has been tentatively postulated by Crosby who states (1960, p. 57):

> " - in the absence of evidence to the contrary, it is perhaps simplest to regard them (amphibolites) as intrusives of Kaslo age."

Unfortunately, no chemical analyses appear to be available for comparison of the Kaslo intrusives with those of the Kootenay Lake amphibolites.

Recently, notable work has been undertaken by Leake and Evans in an attempt to establish chemical differences that might exist between ortho and para-amphibolites. Leake (1964, p. 242) has presented an interesting method of

plotting major element constituents of amphibolites. He uses a combination of the Niggli values 100 mg, c, and al - alk as the co-ordinates of a triangular diagram. Leake contends that in such a plot, the trends of both igneous rocks and mixtures of pelite and semipelite with limestone (the "ingredients" of para-amphibolites) are different and distinguishable.

A plot of the Kootenay Lake amphibolites, both garnetiferous and non-garnetiferous, has been made using the co-ordinates suggested by Leake; this is presented in Fig. 9A. Fig. 9B (inset) shows Leake's initial plot demonstrating the different trends of a typical series of basaltic igneous rocks (the Karoo dolerites), pelites and semipelites. The dolomite-pelite-limestone lines, and the trend of the Karoo dolerites are transposed on Fig. 9A. The Kootenay Lake amphibolites plot along the igneous trend and may well be ortho-amphibolites. However, Leake has pointed out that,

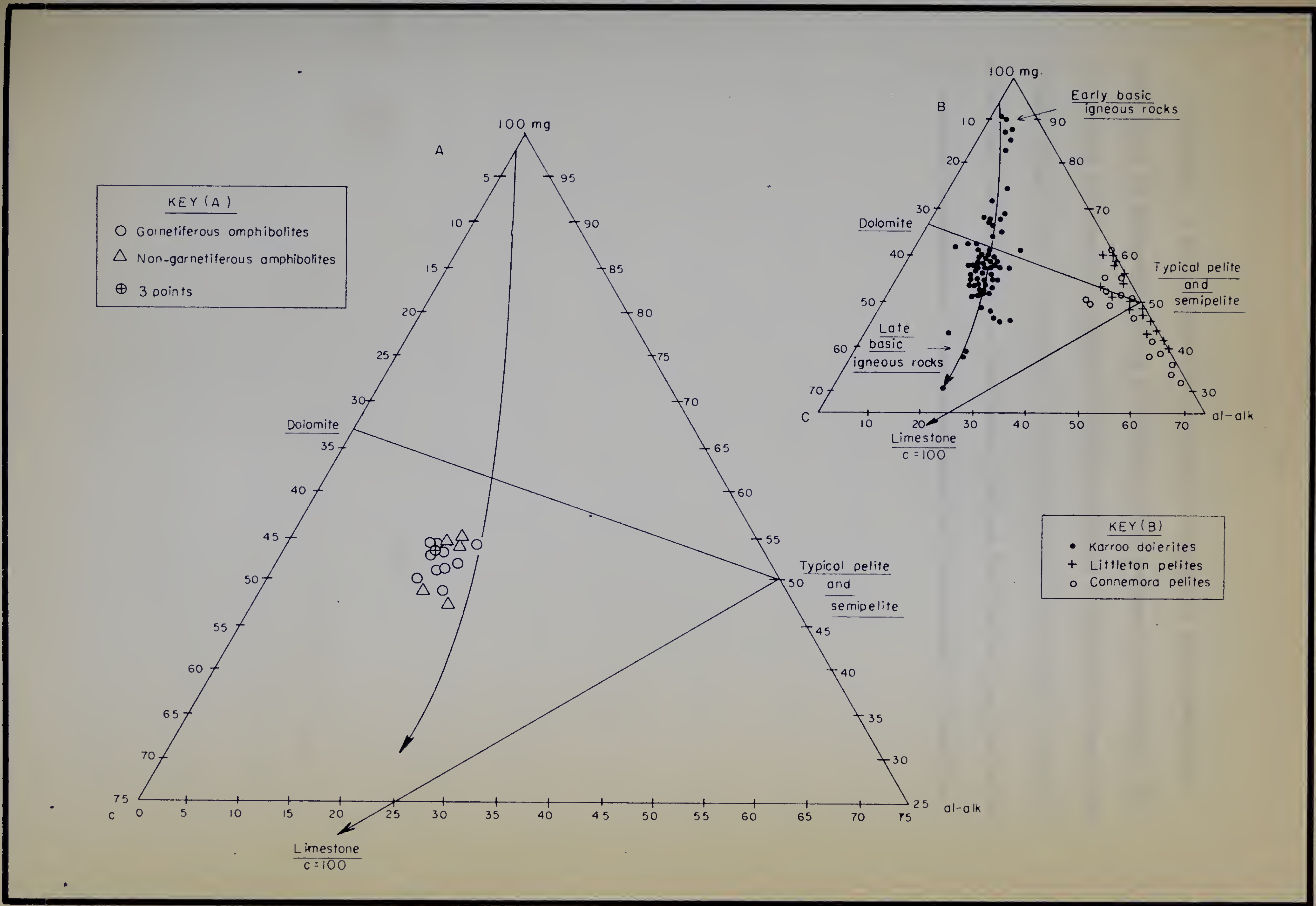
> "Even though a rather unusual series of mixtures of dolomite, limestone, and pelite might conceivably plot parallel to the igneous trend it is difficult to see how any sedimentary rock can plot appreciably above the dolomite-pelite line, whereas many basic igneous and amphibolites do plot in this position."

Since the Kootenay Lake amphibolites plot below the dolomite-pelite line, it appears to the writer that these rocks can still not be regarded unequivocably as ortho-amphibolites, and may represent that "unusual" admixture of sedimentary components.

No further plots were made after Leake, involving such parameters as Niggli mg versus k, ti, or alk, because without the further substantiation of trace element analyses such as Ni, Co, and Cr, these plots are limited in their usefulness.

Figure 9. (A) Part of Leake's 100 mg, c, and (al – alk) triangular diagram, upon which analyses of the Kootenay Lake amphibolites are plotted. Trend line of the Karroo dolerites, and join lines, dolomite – typical pelite and semipelite – limestone, are transposed from diagram

(B) after Leake (1964).



KEY (A)
Garnetiferous amphibolites
Non-garnetiferous amphibolites
3 points
A
100 mg
Dolomite
Typical pelite and semipelite
Limestone c=100
al-alk
c
B
100 mg.
Early basic igneous rocks
Late basic igneous rocks
KEY (B)
Karroo dolerites
Littleton pelites
Connemora pelites

Figure 9.

In summary, it may be stated that although the Kootenay Lake amphibolites studied may be para-amphibolites of a rather unusual sedimentary parentage, the writer tends to favour the suggestion that they represent metamorphosed equivalents of basic igneous rocks, conceivably as has been pointed out by Crosby, relatable to the Kaslo intrusives. The writer does not believe that the rock type was derived by metasomatic replacement of carbonate layers or by metamorphic segregation.

CHAPTER IV

A STUDY OF THE GARNETS

GARNET OCCURRENCE

The areal distribution of garnet-bearing rocks is quite extensive, as shown by the specimen location map Fig. 5.

Garnets are fairly abundant in amphibolites throughout the Lardeau Series on the eastern side of Kootenay Lake. They were found with one exception (167-64), to be lacking along the Canadian Pacific Railway sections examined between Proctor and Wilson Creek within this series. Garnet-bearing amphibolites were not seen by the writer in the younger series on the western side of the Lake. In the amphibolites where garnets do occur, they have a relatively homogeneous distribution. In small amphibolite bodies garnets are prominent throughout, but in the much larger bodies (eg. those occurring in the road section along Highway 3, between Crawford Bay and Kootenay Bay), they are mainly confined to the peripheral portions with a somewhat sparse distribution within the cores.

In the schists, garnets are most plentiful within the Plaid Lake Formation and formations younger than the Deanshaven, within the central Kootenay Lake map area. Intercalated schists within the Lardeau Series are fairly rare, but are garnetiferous. The gneisses of the Bluebell Formation carry very little garnet - a fact also mentioned by Crosby (p. 66). Where garnet is present

within the schists, it is highly variable in size and distribution. Garnet porphyroblasts up to a size of 3" were observed within the Lardeau Series in Tam O'Shanter Creek.

Acid igneous material, especially the Kootenay Intrusives, are notably peraluminous, and generally carry abundant garnet. In these rocks, garnet forms as minute, relatively euhedral megacrysts, which are distributed throughout. This may well be the result of assimilation of sedimentary material, as is suggested by the occurrence of garnets developed in a "halo-like" pattern about an almost completely "digested" xenolith at one locality. The following is a more detailed discussion of garnets from the three rock types and concerns colour, form, texture and associated minerals. Plates 3 to 6 show some of the features mentioned in hand specimen and from thin sections.

GARNETS FROM AMPHIBOLITES

In reflected light, the garnets from amphibolites are generally subtle shades of orange-brown variably tinged with pink. The nearest tone apparently equivalent to Ridgeway's (1912) colour disks, would probably be vinaceous-russet. Specimen 65-64 is probably the most different in colour, having a decidedly richer shade of orange-brown. Transparency appears good in all cases. In thin section, garnets are generally pale pink in colour.

Garnets are generally quite variable in size, even within the individual

PLATE 3

HAND SPECIMEN PHOTOGRAPHS OF GARNETIFEROUS KOOTENAY LAKE AMPHIBOLITES

a) Specimen 109a-64: Large idioblastic garnets set in a medium grained, hornblende, plagioclase, and quartz matrix.

b) Specimen 109-64: From the same locality as specimen 109a-64. Relatively homogeneously distributed, xenoblastic garnets. Matrix composed predominantly of hornblende, plagioclase, and quartz.

c) Specimen 77-64: Xenoblastic garnets of variable size. Matrix predominantly composed of hornblende.

d) Specimen 77a-64: From the same locality as specimen 77-64. Abounds with xenoblastic garnets, of highly variable grain size. Stringers on the right-hand side of the specimen, consist entirely of garnet. Matrix composed of hornblende and plagioclase.

e) Specimen 86-64: Small xenoblastic garnets set in a well lineated predominantly hornblende plagioclase matrix. Concordant, thin quartz vein on the right-hand side of the specimen.

f) Specimen 12-63: Xenoblastic garnets. Matrix composed mainly of hornblende, plagioclase and quartz.

g) Specimen 28c-63: Xenoblastic garnets of variable grain size. Matrix consists predominantly of hornblende, plagioclase, quartz, and biotite. Specimen cut by a concordant quartz stringer.

h) Specimen 119-64: Strongly corroded garnets set in a mainly hornblende, plagioclase, matrix. Pseudomorphing of idioblastic garnet is visible, the outlines of which are composed predominantly of plagioclase with some quartz.

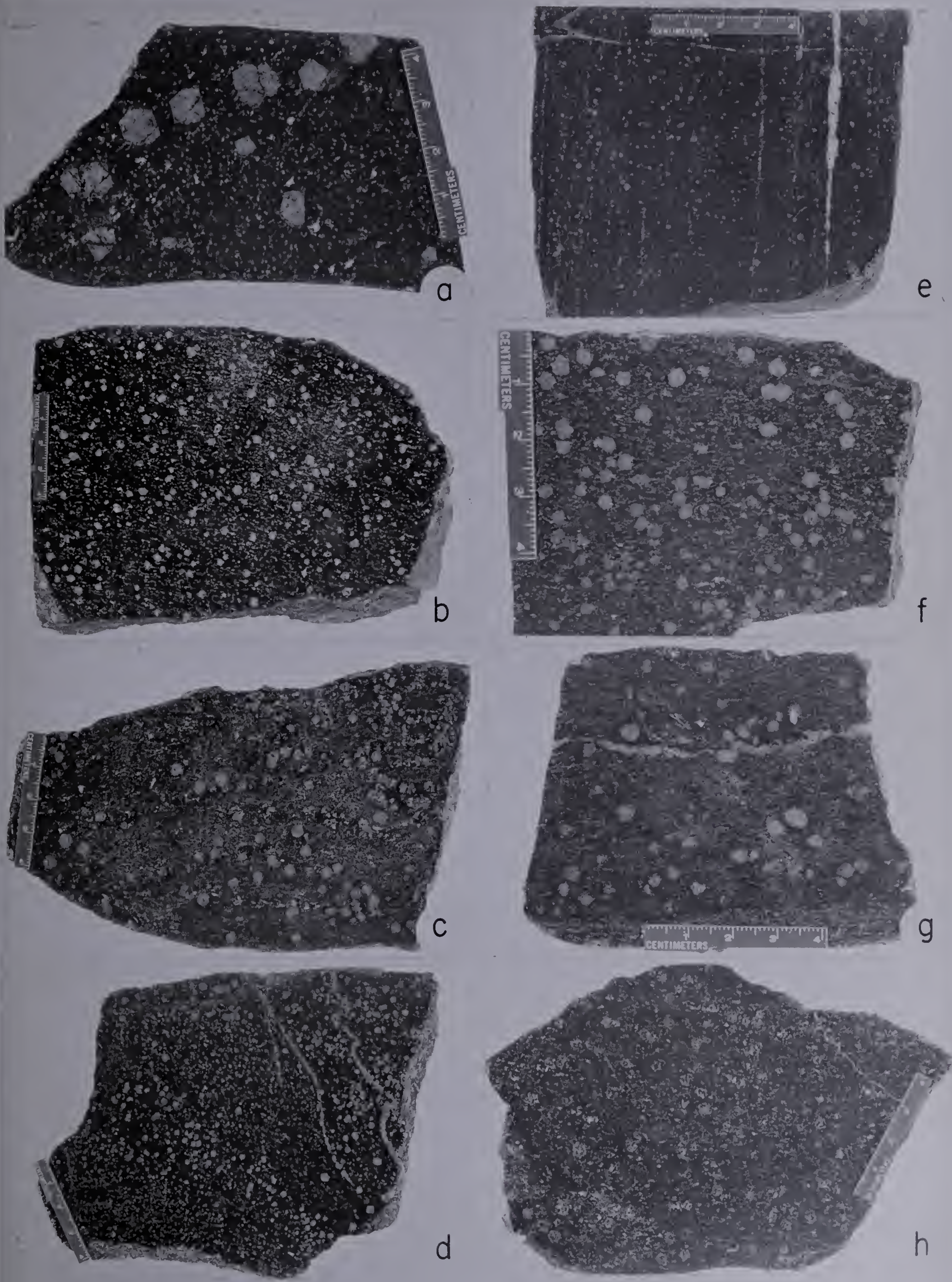


PLATE 3.

PHOTOMICROGRAPHS OF KOOTENAY LAKE AMPHIBOLITES, BOTH GARNETIFEROUS AND NON-GARNETIFEROUS

(All photographs taken in plane light, and at a magnification of X 10)

a) Specimen 5-64: Small, somewhat poikiloblastic garnets in top right hand corner; devoid of any alteration rim. Matrix composed mainly of stout, fresh hornblende laths, fresh plagioclase (sodic andesine) and quartz. Granular sphene aggregates, at centre of photograph.

b) Specimen 4-64: Non-garnetiferous amphibolite, consisting of stubby xenoblastic hornblende (corroded terminations), slightly sericitised plagioclase (sodic labradorite), and granular quartz.

c) Specimen 28c-63: Strongly corroded poikiloblastic garnets containing alteration rims. Rims composed of plagioclase and quartz, together with abundant orange-brown biotite. Matrix consists of ragged hornblende laths, in part being replaced by biotite (lower edge, centre), plagioclase (sodic labradorite), and quartz.

d) Specimen 28h-63: Non-garnetiferous amphibolite, consisting of large, fresh laths of hornblende, with minor replacement by orange-brown biotite, together with fresh plagioclase (calcic labradorite), and quartz.

e) Specimen 12-63: Xenoblastic garnets, devoid of alteration rims. Matrix composed of stubby, fresh hornblende laths and basal prisms, plagioclase (sodic andesine), and quartz, with very minor orange-brown biotite.

f) Specimen 77-64: Poikiloblastic garnets with thinly developed alteration rims. Latter consist of plagioclase, quartz, with minor biotite, and pale green hornblende. Matrix composed of stout, fresh laths of hornblende, and minor plagioclase (calcic andesine), quartz, and aggregates of granular sphene.

g) Specimen 65-64: A large porphyroblastic garnet comprising almost two-thirds of the photograph. Matrix shows well aligned hornblende, with strongly sericitised plagioclase (calcic andesine), and granular quartz.

h) Specimen 86-64: Xenoblastic garnets with thinly developed alteration rims. Rims contain orange-brown biotite, plagioclase, and quartz. Matrix consists of fresh, somewhat slender hornblende laths, plagioclase (sodic labradorite), quartz, and is finely speckled with opaque ore

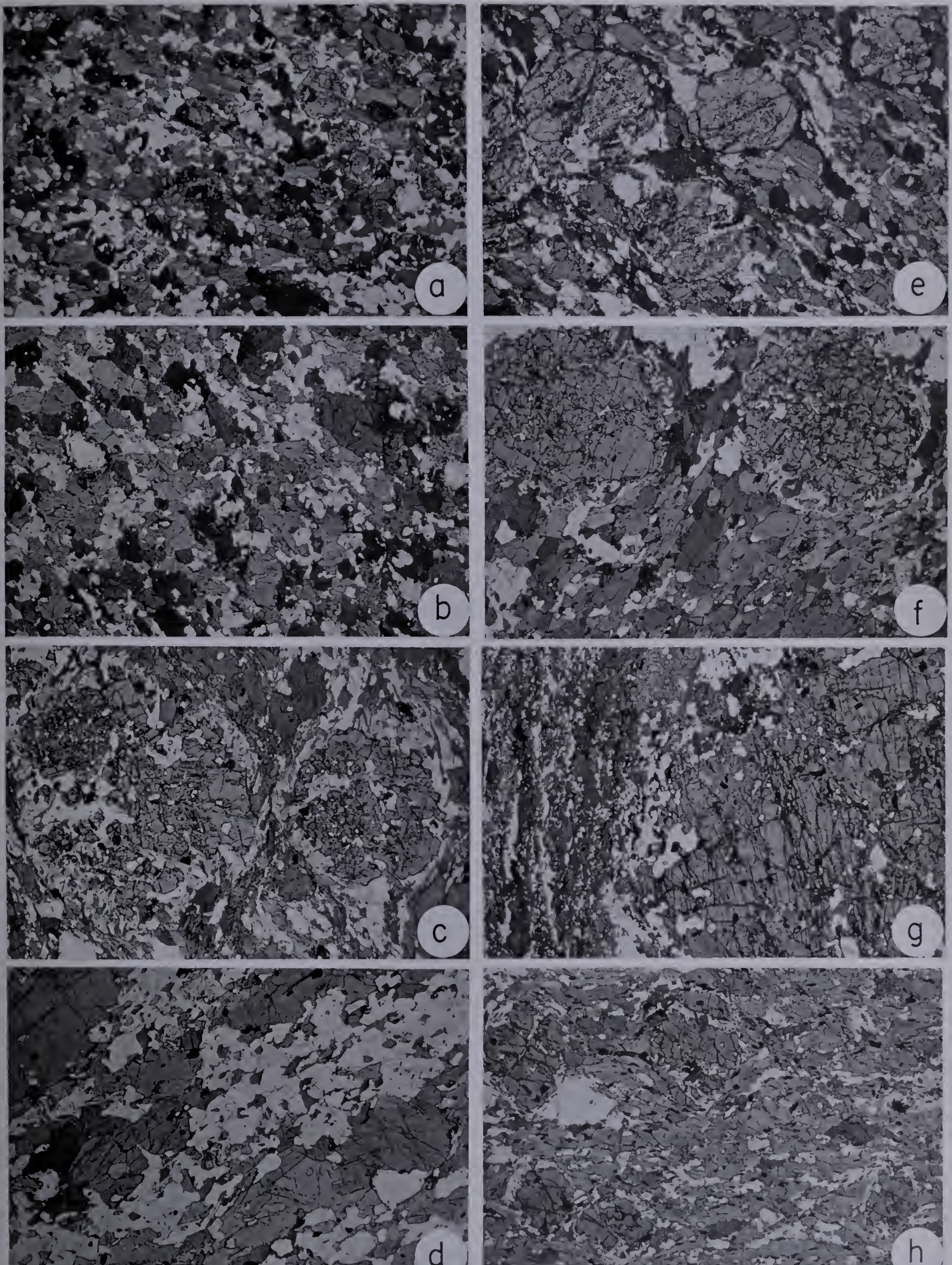


PLATE 4.

PHOTOMICROGRAPHS OF FEATURES ILLUSTRATING INSTABILITY IN GARNETS FROM THE KOOTENAY LAKE AMPHIBOLITES
(All photographs taken in plane light, and at a magnification of X 10)

a) Specimen 28e-63: Collected from the same locality as specimen 28c-63. Strongly corroded garnet poikiloblasts, exhibiting well developed alteration rims. Former, approximately idioblastic shape of garnets is outlined by the rims, which are composed of slightly sericitised plagioclase, quartz, and abundant randomly oriented orange-brown biotite. Matrix consists of ragged, stubby hornblende laths (in part replaced by biotite), fairly fresh plagioclase, and quartz.

b) Specimen 4-63: Partially corroded garnet (bottom right corner), with narrow, poorly defined, alteration rim. Latter composed of relatively fresh plagioclase, quartz, and slender flakes of orange-brown biotite. Felsic-rich patches at left, consist of plagioclase, quartz, and biotite, together with small fragments of garnet. Matrix contains small, well aligned hornblende laths, granular, slightly sericitised plagioclase (calcic andesine), and quartz. Stringers of opaque ores are prominent.

c) Specimen 35-64: Strongly corroded, poikiloblastic garnet, exhibiting partial to almost complete pseudomorphing of idioblastic garnet. Rims and embayments of garnet, in lower left corner, consist of somewhat randomly oriented plagioclase laths, orange-brown biotite and quartz. Upper right corner, illustrates almost complete pseudomorphing of garnet, where all that remains are minute fragments of garnet (top corner) set in a plagioclase, quartz, biotite mosaic. Matrix lacks biotite, and is composed of stubby, fresh, ragged laths of hornblende, plagioclase (sodic andesine), and quartz.

d) Specimen 35-64: Same specimen as in (c), illustrating similar partial to almost complete pseudomorphing of garnets.

e) Specimen 7-64: Corroded garnet poikiloblast, enclosed by an elliptical shaped alteration rim composed predominantly of randomly oriented fresh plagioclase, together with quartz, and slender blades of secondary bluish-green hornblende, and very minor granular epidote. Matrix consists of hornblende, unaltered plagioclase, and quartz.

f) Specimen 109-64: Alteration rims enveloping corroded, poikiloblastic garnets. Rims composed of plagioclase, quartz, minor calcite, and a few flakes of pale-green chlorite. Matrix comprises mainly hornblende, plagioclase (sodic andesine), and quartz; minor calcite.

g) Specimen 92-64: Corroded poikiloblastic garnets, exhibiting felsic-rich alteration rims, containing plagioclase, biotite, and quartz. Matrix consists mainly of fresh hornblende, plagioclase, and quartz.

h) Specimen 180-64: Felsic-rich patches, probably pseudomorphs of garnet. The patches consist predominantly of interlocking, somewhat randomly oriented plagioclase laths, together with quartz, minor biotite, and rare minute granules of epidote. Garnet is completely absent. The pronouncedly hornfelsed matrix contains mainly hornblende,

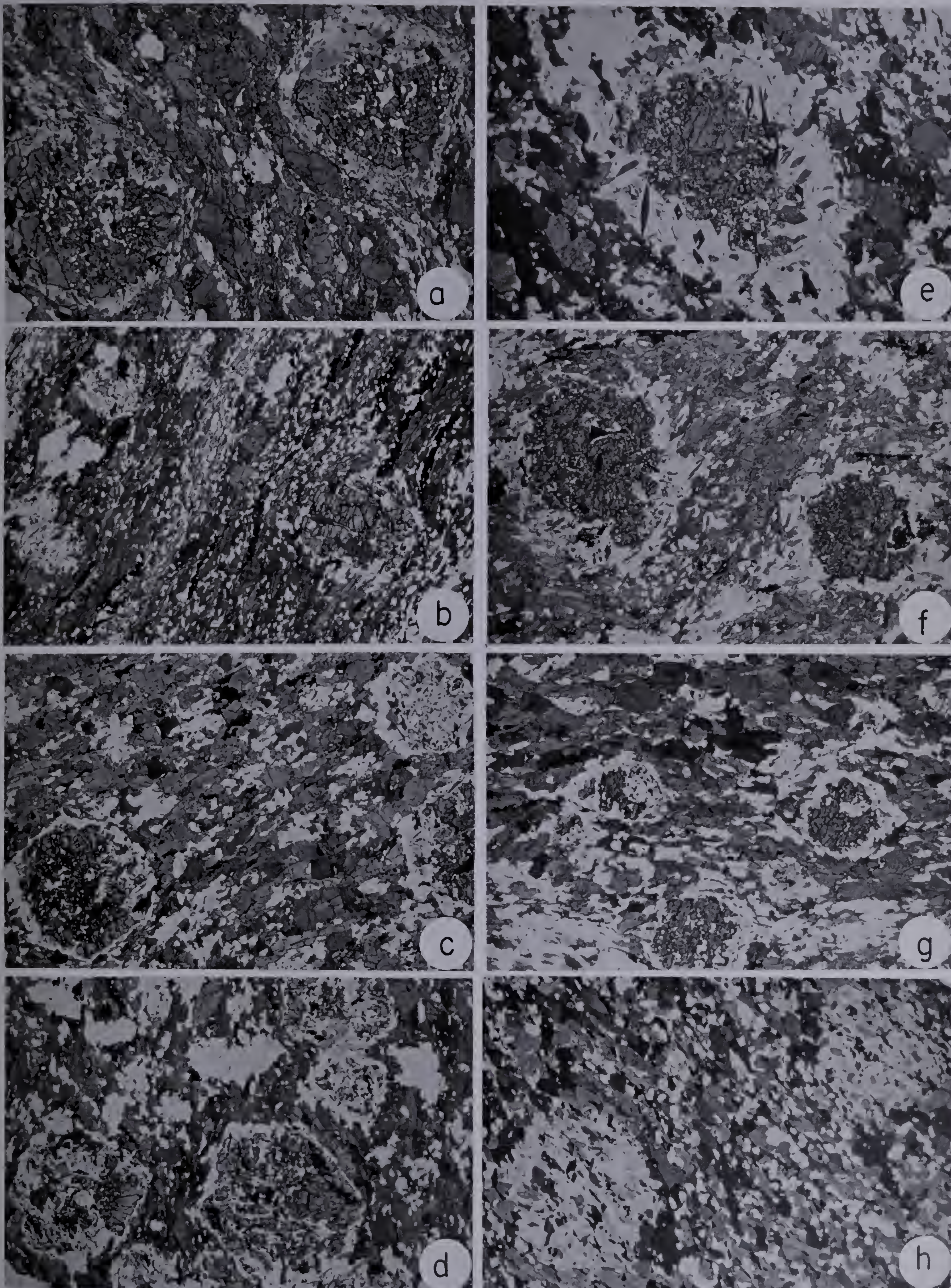


PLATE 5.

HAND SPECIMEN PHOTOGRAPHS, AND PHOTOMICROGRAPHS OF GARNETIFEROUS SCHISTS, AND A GARNETIFEROUS APLITE FROM THE KOOTENAY LAKE AREA

(All photomicrographs taken in plane light, and at a magnification of X 10)

a) Specimen 2-63: (hand specimen). Large xenoblastic garnets set in a matrix of quartz, biotite, and muscovite. Crenulations are readily visible, owing to the moderately well defined biotite, muscovite, and quartz-rich "inter-layers".

b) Specimen 2-63: (photomicrographs). Large corroded poikiloblast of garnet, in which shallow S-shaped trends, imparted by predominantly quartz inclusions, are discernable. The trends are notably perpendicular to the schistosity of the matrix. A "shadow zone" of randomly oriented, red-brown biotite is visible at the lower right.

c) Specimen 1-63: (photomicrograph). Part of a large corroded poikiloblastic garnet, exhibiting a well developed "shadow zone" composed predominantly of randomly oriented red-brown biotite, together with several small fragments of garnet. The "zone" tapers, and is drawn into the crenulations in the matrix (bottom right corner).

d) Specimen 31a-63: (photomicrograph). Corroded garnet porphyroblasts, containing mantles of red-brown biotite. Biotite is partially replaced by swirls of fine, acicular sillimanite (fibrolite). Matrix is composed of slender flakes of biotite and muscovite, together with abundant quartz.

e) Specimen 145-64: (hand specimen). A large staurolite idioblast, together with several smaller ones, set in a fine-grained, hornfelsed matrix mainly composed of quartz, chlorite, and biotite. Minute dark specks, profusely scattered throughout, are garnet xenoblasts.

f) Specimen 145-64: (photomicrograph). Large corroded porphyroblast of staurolite, at the left, is enveloped by an alteration rim comprising an inner zone of finely matted white mica, and a narrower outer zone of pale-green chlorite. Flakes in both zones are randomly oriented. Five xenoblasts of garnet (several thinly mantled by chlorite), are also featured, one of which is enclosed within the staurolite. The matrix is pronouncedly hornfelsed.

g) Specimen 136a-64: (photomicrograph). Several, somewhat elongate garnet xenoblasts, enveloped by thin mantles of chlorite flakes. Ovoid patches, at right and left, are composed of finely matted white mica and chlorite flakes (darker portions), and may possibly represent completely altered staurolite. Flakes of both minerals are randomly oriented. Matrix, which is fine-grained and pronouncedly hornfelsed, consists mainly of quartz, corroded biotite, and abundant chlorite.

h) Specimen 22-63: (photomicrograph). Garnet-bearing aplite, with euhedral to

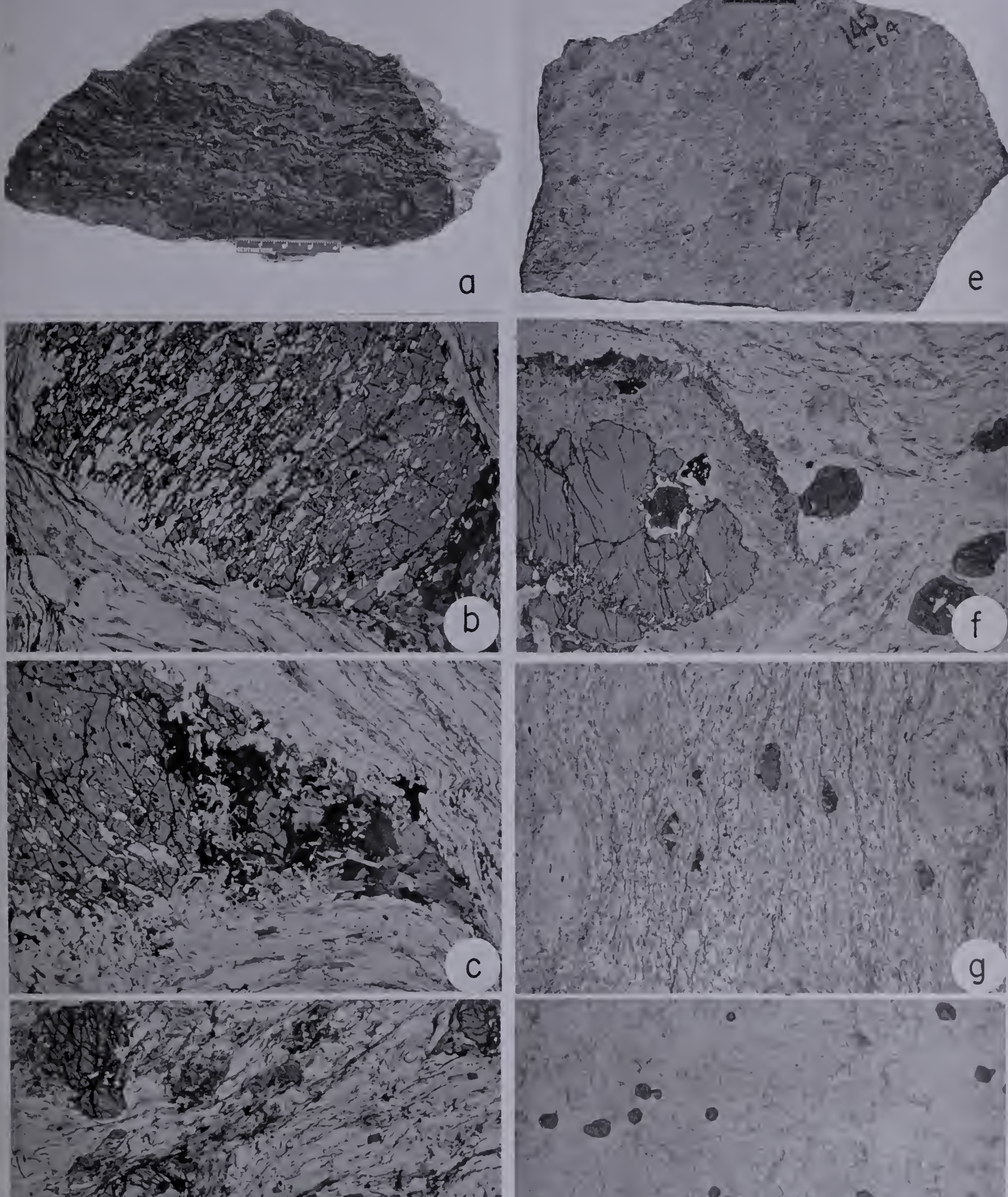


PLATE 6.

amphibolite bodies. This is well demonstrated in the Plates of hand specimen photographs. Size usually ranges from 1 to 3 mm., although in two specimens (109-64 and 65-64), garnets up to 10 and 20 mm. were observed. In form garnets range from idioblastic to strongly xenoblastic. Grains are generally well rounded to angular and ragged (corroded), occasionally elongate (ovoid) and agglomero-porphyroblastic.

All garnets are to varying degrees poikiloblastic in texture. Inclusions, which ubiquitously seive most of the garnets, are predominantly quartz granules, but also include highly variable amounts of sphene, plagioclase, and opaque ores. Certain garnets exhibit marginally, areas which are almost devoid of included minerals. Trends of inclusions suggesting movement (rotation) of porphyroblasts during growth were not observed in any of the garnets from amphibolites. The odd garnet appears to show signs of rapid growth, giving rise to "bowing" of the enveloping schistosity.

An interesting and illuminating feature prevalent in garnets from amphibolites, is the development of felsic-rich rims or selvages usually occurring where garnets are somewhat corroded. The degree to which these felsic-rich margins are developed, appears to increase with the amount of corrosion of the garnets, and probably represents partial to complete breakdown of the garnet porphyroblasts. All stages of breakdown are visible within the examined garnets and can even be observed within individual amphibolite specimens. Specimen 35-64 illustrates particularly well the features of partial pseudomorphing after garnet. In this case, felsic-rich selvages enveloping the porphyroblasts, outline the idioblastic shapes of now corroded grains of garnet. In specimen 180-64, breakdown is complete -

the amphibolite has a "spotted" appearance as a result of the pseudomorphing after garnet. No signs of relict garnet were observed when this rock was examined under the microscope. Remaining are knots of interlocking plagioclase laths, dotted with granular quartz, randomly arranged small biotite flakes, and the occasional rare minute granule of epidote. It is notable that "spotted" amphibolites were observed in several localities along the Canadian Pacific Railway section south of Procter. Garnet breakdown may partly account for the lack of garnetiferous amphibolites in this area.

The felsic-rich rims and corroded garnet porphyroblasts are invariably associated with flakes of pleochroic orange-brown biotite. These flakes are usually small, randomly oriented, and develop peripherally and within the embayments between "fragmental" garnet. Chlorite occurs only in minor amounts in the amphibolites, and is generally associated with garnet. It forms small, randomly oriented pale green flakes, and usually develops peripherally against, or more rarely as minute veinlets "intruding" garnet. Calcite is exceedingly minor in association with garnet porphyroblasts, and appears restricted to one specimen (viz. 109-64). Epidote is trivially associated with garnet, or the felsic-rich patches which are pseudomorphed after garnet.

It was previously pointed out (p.37) that hornblende developing peripherally and also within the felsic-rich rims of certain of the altered garnet porphyroblasts, is characteristically faintly pleochroic pale bluish-green. Green-brown hornblende, within these particular amphibolites, has also been marginally tinged a similar bluish-green colour.

GARNETS FROM SCHISTS

The colour of these garnets in reflected light is more variable than those from the amphibolites. All have a purplish colour, varying from drab purple to a more vivid reddish purple (vinaceous), but are difficult to match with Ridgeway's colour disks. Reddish tinged garnets exhibit good transparency, but the drab purple varieties are somewhat translucent by comparison. In thin section, garnets are pale pinkish to purplish.

Grain size is highly variable in the eight garnets examined in detail, ranging from 4 to 15 mm. in specimens 1-63 and 2-63 to 0.3 - 0.5 in 136-64. Garnets are generally xenoblastic in form, occurring as rounded, elongate (ovoid), angular, and somewhat ragged (corroded), grains.

The garnets are slightly to highly poikiloblastic in texture. Quartz is by far the most common included mineral; granular opaque ores and plagioclase are relatively minor by comparison. Two schists 1-63 and 2-63, contain garnets in which inclusions show shallow "S-shaped" trends. This indicates a certain degree of rotation of the porphyroblasts at some stage during their growth. Trends of the inclusions are opposed to those of the crenulations or microfolding in the enveloping quartz-mica "matrix", which suggest that the garnet grew at some earlier stage, prior to the development of the microfolds themselves. Breakdown of the garnet has resulted in the formation of red brown biotite, the flakes of which are randomly distributed around the garnet. Since the biotite flakes are partially drawn out and incorporated in the "matrix" crenulations, it is advocated that corrosion of the garnet must have taken place at some stage prior to, or early during the deformation producing the crenulations.

Red brown pleochroic biotite is also associated with garnets in specimens 31a-63, 57-64, 152-64. In 31a-63, biotite developing about corroded garnet porphyroblasts is invaded by swirls of fine acicular sillimanite (fibrolite). In specimens 136a-64 and 145-64, corroded garnet is enveloped by pleochroic, pale green chlorite, and occasionally patchworks of fine white mica.

GARNETS FROM ACID IGNEOUS VEINS

The colour of these garnets are decidedly deeper than those in either the amphibolites or the schists. Specimen 22-63 is a deep red brown, probably claret brown on Ridgeway's colour disks. Specimen 5-63 is pinkish red brown, much lighter than specimen 22-63. Both show fairly good transparency and appear pale pink in thin section.

Both usually have a grain size less than 1 mm., generally ranging from 0.2 to 0.5 mm. The grains vary from almost idioblastic to xenoblastic, are almost entirely devoid of inclusions, and are unaltered.

SEPARATION AND ANALYTICAL PROCEDURES

SEPARATION PROCEDURE

The separation of garnet for chemical analyses and physical parameter determination was achieved essentially by means of mechanical breakdown, concentration by use of a Frantz Isodynamic Separator and heavy liquids (diiodomethane and Clerici's solution), and finally, by hand picking.

Samples were first cleaned of any oxidised portions, using a diamond saw. Reduction of this material was then made by way of a "jaw crusher". After

separation of a portion, by quartering, for whole-rock chemical analyses, the remainder was further reduced using a Braun mill. This material was screened using a series of seives ranging from 80 to 140 mesh in size. At this stage, any iron filings liberated from the Braun mill, were removed. This was accomplished by means of a hand magnet.

The garnets from the seived fractions were first concentrated using the Frantz Isodynamic Separator. It is interesting to note that a preliminary concentration (whereby the majority of felsic material is rapidly removed), can be made by using the Frantz Separator (having removed the tray) in the vertical position at full amperage. The 80 to 120 mesh fractions were reduced to pass through 120 mesh, and collection was made of the mesh range 120 - 140.

Further concentration of this material, containing mainly garnet and/or hornblende and biotite, was achieved using diiodomethane. Since diiodomethane has a specific gravity of only 3.33, which approximates the upper specific gravity limit of hornblende, it was found necessary in several cases to undertake a further separation using Clerici's solution (a solution of the salts thallium formate and thallium malonate, specific gravity 4.2), in order to achieve a reasonable result.

Final concentrates were "hand picked" beneath the binocular microscope. Approximately 1 to 1 1/2 gm. quantities were separated from each garnet sample.

Due to the extremely poikiloblastic nature of the garnets, complete removal of all included mineral grains is an exceedingly difficult task. As a consequence, criticism may be levelled on the grounds that the garnets were not reduced further in mesh size than 140. The writer, however, felt that any further reduction in size would have made heavy liquid separation and "hand picking" an even more

arduous undertaking.

Garnet grains from separates were mounted in a liquid approximating their index of refraction, and examined under the petrographic microscope. The writer estimated that the degree of "purity" of the garnets was close to 95%.

ANALYTICAL PROCEDURE ADOPTED

Partial chemical analyses were undertaken for twenty garnets, 13 from amphibolites, 5 from schists, and 2 from acid veins. Fe_2O_3, FeO, MnO, MgO, and CaO determinations were made in all cases; further analyses for TiO_2, SiO_2, and Al_2O_3 were undertaken on two of the garnets from amphibolites. Total Fe_2O_3, CaO, MnO, MgO, TiO_2, SiO_2 and Al_2O_3 were determined with some modifications using the "main portion" procedure of standard wet chemical analyses (Baadsgaard, 1960; Groves, 1951). The modified Rowledge method proposed by Groves (p. 184), was adopted for FeO and separate samples run for this determination. In view of the time consuming process involved in garnet separation, especially the hand picking aspect, it was decided to use minimal quantities for chemical work. Of the 1 to 1 1/2 gm. separated, 0.5 - 0.6 gm. were used for the "main-portion" analyses and 0.2 - 0.3 gm. for that of the FeO. Batches of four garnet samples were run consecutively and proved manageable.

FERROUS AND FERRIC IRON

The analysis of FeO is that subject to most difficulties. Many attempts have been made to obtain accurate values for FeO, especially in the case of refractory minerals (Rowledge, 1934; Hey, 1941; Groves, 1951; Wilson, 1955; Reichen, 1962). The Pratt method (most commonly used for FeO determination) described by

Groves (p. 90-91), fails on account of incomplete decomposition of refractory minerals (including garnet - the writer found this to be so, even after heating 3 to 4 times longer than recommended). Consequently, the writer resorted to Groves modification of the Rowledge method (p. 184). Certain drawbacks can be met within this method, and these are pointed out in Appendix B. Check runs were made on the procedure and Table II shows the results.

Table II. FeO Determination by Modified Rowledge Method - Reproducibility

	FeO (Wt. per cent)		
	1	2	3
5-63	28.70	28.47	28.51
22-63	25.83	25.54	25.55
*W.1.	8.70	8.65	

*Value accepted for W.1. is 8.74%, Fleischer and Stevens (1962)

Decomposition of garnet was found to be excellent in all cases using this procedure, and agreement with the W.1. results of Fleischer (1962) was reasonable. It was felt, however, that even this method is likely to give somewhat low values for FeO as a result of oxidation, since the temperature required for adequate fusion was about 1000°C and the time for dissolving the fused sample about 2 hrs. Although these two processes were carried out in a supposedly inert atmosphere (using nitrogen purged of oxygen by bubbling through pyrogallol), the chance of some oxidation of the FeO is quite high and must be considered.

The determination of total Fe_2O_3 was made directly on the R_2O_3 precipitate. This was accomplished by acidifying the precipitate, and titrating, potentiometrically,

with standard potassium chromate solution. Ferric iron was calculated using the appropriate gravimetric conversion factor, from the total Fe_2O_3 and FeO values. It should be noted that a low value of FeO will obviously cause the Fe_2O_3 to be high.

MANGANESE

Manganese was removed as the sulphide following the R_2O_3 precipitation using the method of ammonium sulphide precipitation after Hillebrand et al., (1962, p. 64). The removal of manganese at this stage was found necessary due to interference (the exact cause of this was not clearly understood) in the magnesium precipitation possibly by manganese, especially in the case of the spessartite-rich garnets from acid veins. Manganese was then precipitated as manganese ammonium phosphate, ignited to the pyrophosphate, and determined gravimetrically. Small amounts of manganese passing through the ammonium sulphide precipitation would be precipitated mainly along with magnesium as the ammonium phosphate, and the remainder with calcium as the oxalate. These small amounts of manganese were then determined colourimetrically. Colourimetric checks run on the manganese ammonium phosphate precipitate were good.

CALCIUM AND MAGNESIUM

Both calcium and magnesium analyses were made using standard gravimetric wet chemical procedures. Calcium was precipitated as the oxalate and ignited to the oxide, and magnesium precipitated as the ammonium phosphate and ignited to the pyrophosphate.

Analytical results for garnets from amphibolites are shown in Table 13, and

those for garnets from schists and acid veins in Table 15. The more complete results for two garnets from amphibolites are shown in Table 18. Two further analyses from schists after Crosby (1960), are presented in Table 17.

CALCULATION OF MOLECULAR COMPOSITION OF GARNETS

Garnets may usually be considered as a five-component series including almandite, andradite, grossularite, pyrope and spessartite.

Almandite	$Fe_3Al_2(SiO_4)_3$	Grossularite	$Ca_3Al_2(SiO_4)_3$
Spessartite	$Mn_3Al_2(SiO_4)_3$	Andradite	$Ca_3Fe_2(SiO_4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$		

99% or more of most garnets encountered can be represented in terms of these five end-member molecules. Uvarovite, the chrome calcium garnet, is the only other notable end-member, but this is very rare in occurrence.

Molecular compositions have been determined for twenty garnets, and these are recorded in Tables 13 and 15. Due to the "minimal" number of analyses, the determination of molecular composition relies heavily on the accuracies of these analyses. In the actual calculation, the assumption is made that all FeO is attributable to almandite, MnO to spessartite, MgO to pyrope, and Fe_2O_3 to andradite. After the amount of CaO required to "combine" with all Fe_2O_3 is determined, the remaining CaO is allotted to grossularite.

PHYSICAL PARAMETERS OF GARNETS

UNIT CELL PARAMETER MEASUREMENT

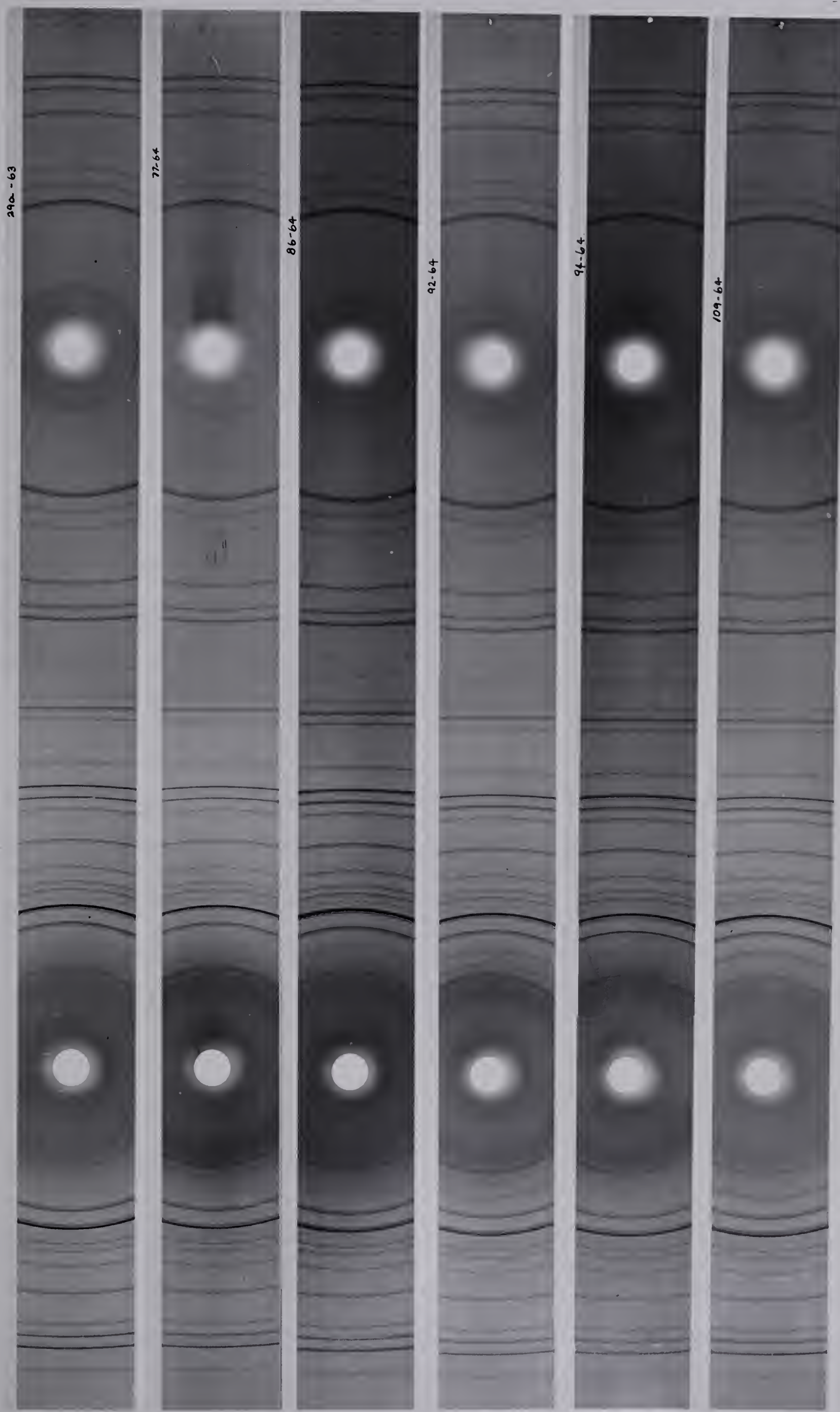
Because of the relatively small available quantities of separated garnet due to the difficult and lengthy process of separation, the writer resorted to the Debye-Scherrer X-ray powder photographic method for the determination of the unit cell parameter of the garnets.

Specimens were mounted in a small ball on fine glass fibres; vaseline was used as the adhesive. The large Philips Debye-Scherrer powder camera (114.6 mm.), designed for the Straumanis technique of film calibration, was used for all photographs, owing to the ease and greater accuracy of measurement of the larger film. Co $K\alpha_1$ radiation ($\lambda = 1.7889$ Å, Fe filter) was used in preference to Cu $K\alpha_1$ radiation, since the latter was found to give rise to "fogging" of the film, especially in the high angle ("back-reflection") region. "Fogging" was probably the result of iron fluorescence (Azaroff and Buerger, 1958, p. 248) since the garnets have a high iron content. Although reducing the number of reflections measurable as a result of its greater wavelength, minimal "fogging" was encountered using Co $K\alpha_1$ radiation. This allowed easier measurement of the high angle reflections, and consequently, a greater accuracy in parameter determination was obtained. Operating conditions for X-ray powder photography are presented in Appendix C.

The photographs (several are illustrated in Plate 7) are typically cubic. The first two or three lines on each photograph (lowest 2θ) were unaccounted for, but could conceivably represent reflections from inclusions (quartz?) within the garnet.

PLATE 7

X-ray powder photographs of Kootenay Lake garnets.


29a-63
77-64
86-64
92-64
94-64
109-64

The remainder of the measured lines correspond to known garnet reflections. Doublets appearing in the low 2θ reflections are obviously not due to resolution of α_1 and α_2; they are probably the result of absorption effects (Azaroff and Buerger, p. 251).

The photographs were measured on a Philips "Norelco" instrument which consists of a strip lighted background, upon which the photographs are mounted. Measurements were made using a travelling vernier scale. The vernier was graduated to 0.05 mm. only, and estimates were made to the nearest 0.025 mm. Following correction for shrinkage during film development, apparent values for unit cell dimensions (a_o) were determined for each $K\alpha_1$ reflection using the relationship

$$a_o = d\sqrt{h^2 + k^2 + 1^2}$$

The Nelson-Riley (1945) extrapolation method was adopted for the derivation of the unit cell dimensions, on the grounds that most errors inherent in determinations using the powder photographic method vanish at $\theta = 90°$ (ie. the position of a reflection in the direction of the incident X-ray beam). Since absorption is a prominent source of error, these authors consider a plot of a_o against the $f(\theta)$,

$$1/2\left(\frac{\cos^2\theta}{\sin^2\theta} + \frac{\cos^2\theta}{\theta}\right)$$

to be the best, because it gives good linearity to reflections at least as low as $\theta = 30°$. Values of a_o were plotted against the function of Bragg angle θ, and the resulting linear curve extrapolated to $\theta = 90°$. This value of a_o is taken as

the unit cell dimension. The unit cell dimension was in actual practice determined by adopting a method of least squares to obtain the best fit straight line to the above plot, using only values of θ ranging between 30°– 90°. Four such plots are illustrated in Figure 10. The difference in the slopes of the plots are, according to Nelson and Riley, attributable to differences in the thickness of the specimen mounts.

Twenty-five cell parameter measurements were made using the above procedure, and the values obtained are recorded in Tables 14^{II} and 16^{II}. A range of errors was found to be ± 0.0007 to 0.002 Å, the error determination being based on the regression of a_o and f(θ) on the best fit straight line. Statistical methods adopted for the determination of unit cell parameter values and errors are presented in Appendix C.

REFRACTIVE INDEX (N) MEASUREMENTS

Indices of refraction of twenty-five garnets were determined by conventional oil immersion techniques using sodium light. Oils used were checked by way of an Abbe Refractometer, and measurements obtained at 23°C were converted to 25°C using the temperature coefficients (dn/dT) recommended by Meyrowitz and Larson (1951).

Results of refractive index measurements are presented in Tables 14^{I} and 16^{I}. Error estimates of results are considered to be ± 0.005.

SPECIFIC GRAVITY

In view of the marked poikiloblastic nature of the garnets examined, the writer considered that the specific granity determinations would be too inexact to

Figure 10. Nelson-Riley extrapolation plots for determination of garnet cell parameters.

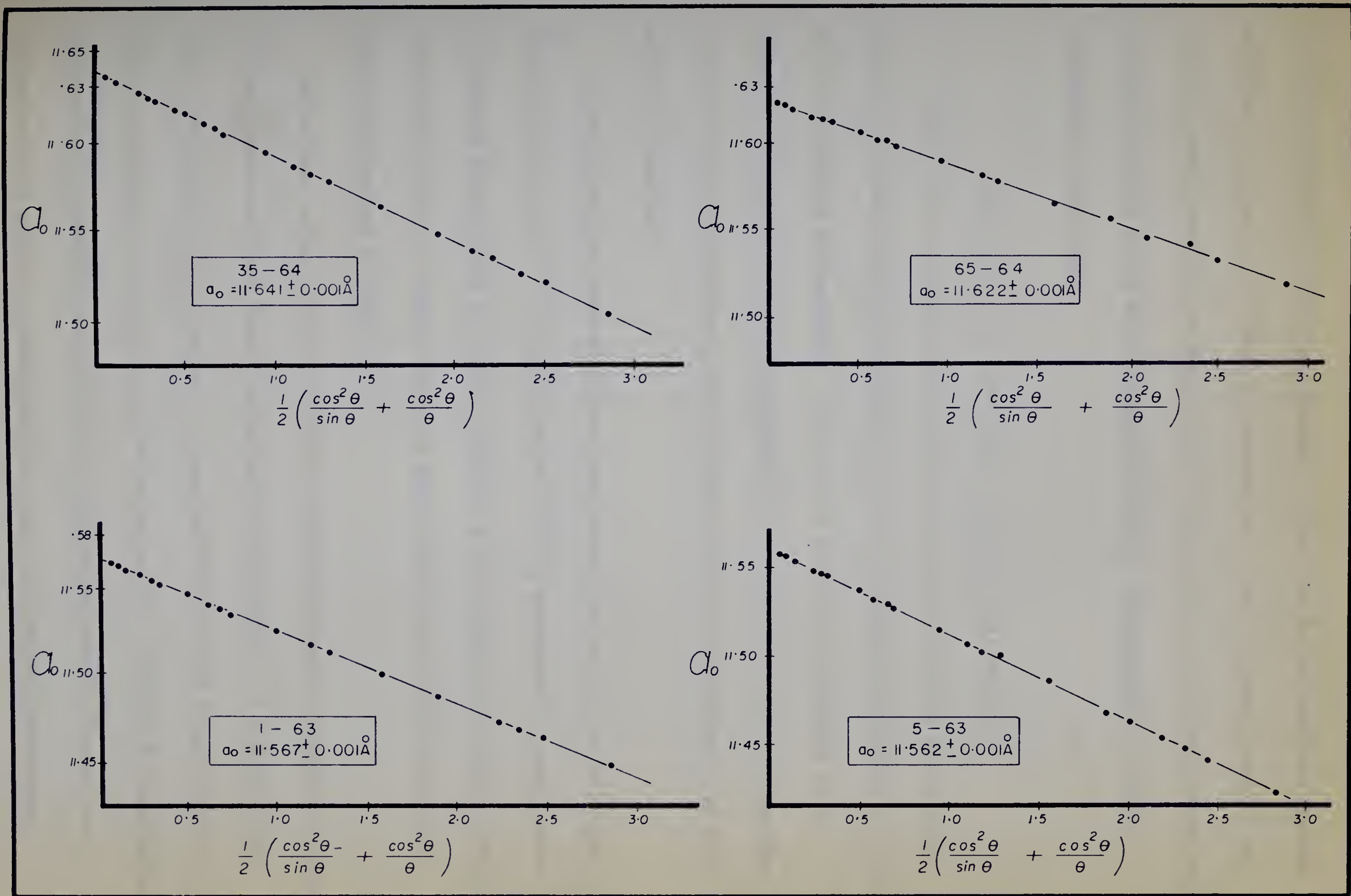

35 – 64
$a_o = 11{\cdot}641 \pm 0{\cdot}001\,Å$
65 – 64
$a_o = 11{\cdot}622 \pm 0{\cdot}001\,Å$
1 – 63
$a_o = 11{\cdot}567 \pm 0{\cdot}001\,Å$
5 – 63
$a_o = 11{\cdot}562 \pm 0{\cdot}001\,Å$
a_o
$\frac{1}{2}\left(\frac{\cos^2\theta}{\sin\theta} + \frac{\cos^2\theta}{\theta}\right)$

Figure 10.

merit the undertaking of their measurement. Even had the garnets been crushed sufficiently in order to facilitate the removal of all the included minerals, the resulting powder would have been of such a fineness that an accurate determination of specific gravity would be exceedingly difficult. Consequently, no such measurements were made.

RELIABILITY OF CHEMICAL ANALYTICAL RESULTS

A useful check of chemical analytical results can be obtained by using the determined values of physical parameters (ie. unit cell edge and refractive index) of the pure garnet end-members. Any errors or bias due to inclusions in the chemical analyses should become apparent if a comparison is made between the values of physical parameters calculated from molecular composition, and those directly determined.

Values of physical parameters have been determined for the five major garnet end-members by Ford (1915) and Fleischer (1937) by extrapolation using a series of analysed garnets, and by Skinner (1956) by direct measurement of pure synthetic end-member garnets. These values plus those of Stockwell (1927) for unit cell edges are presented in Table 12.

Using these values, it is only a matter of simple arithmetic to obtain calculated physical parameters from determined molecular composition. It is to be noted, that in making such a calculation, it is assumed that a strictly linear relation of physical properties between garnet end-members exists. Although this assumption to the writer's knowledge has only been verified experimentally for the two-component solid solution series almandite-pyrope, and grossularite-pyrope

Table 12. Values of unit cell dimensions and refractive index for the five major garnet end-members, at 25°C

	Ford	Stockwell	Fleischer	Skinner	
	N	a_o, Å.	a_o, Å.	N	a_o, Å.
Almandite	1.830	11.516	11.518	1.830	11.526
Spessartite	1.800	11.600	11.613	1.800	11.621
Pyrope	1.705	11.453	11.463	1.714	11.459
Grossularite	1.735	11.864	11.864	1.734	11.851
Andradite	1.895	12.064	12.069	1.887	12.048

(Chinner et al., 1960), the good agreement between the extrapolated values of Ford and Fleischer, and those values obtained by Skinner, would suggest that linearity is probably the case.

Calculated and determined values for the physical parameters of all chemically analysed garnets are to be found in Tables 14 and 16. On the whole, the analyses of garnets from amphibolites would appear to give closer agreement between the determined and calculated physical parameters than those from the schists. The reason for this is not altogether apparent. Discrepancies existing between these two values may be the result of, either inclusions not removed during separation, biasing the chemical analyses, or possibly due to low values of FeO, or to the combination of these two factors. It is felt that errors in the chemical determination of MnO, CaO, total Fe_2O_3, and MgO are probably relatively slight, since good checks were encountered where reruns were made.

Low values for FeO may partly be the cause of the discrepancies. It is

noticeable in all but two cases (ie. those of the unit cell edge of specimens 22-63 and 109-64), that the values of both refractive index and unit cell edge calculated from molecular composition, are greater than those determined directly. If the FeO values are low, this deficiency is attributed to Fe_2O_3. This would consequently give rise to a higher molecular percentage of andradite than is actually present. Since the values of unit cell edge and refractive index for andradite as shown in Table 12 are the highest of the five major garnet end-members, low FeO values (giving rise to a greater andradite content), may partly account for the difference existing between determined and calculated physical parameters. This may perhaps be readily apparent in the two more complete analyses of 5-64 and 35-64 presented in Table 18. Here, the analyses including those for total iron (as Fe_2O_3) are almost identical, save for the FeO and Fe_2O_3 contents. Also, the determined physical properties are almost identical, suggesting a similarity in chemistry between the two analyses. In analysis 5-64, a possible low FeO value and a subsequent high value of Fe_2O_3 may be the cause of noticeably greater values of calculated physical properties than in the case of those determined. The analysis of 35-64, on the other hand, provides almost identical calculated values of physical properties to those measured.

The idealized ratio Si : R^{+3} : R^{+2} for garnets of 3 : 2 : 3, usually approximated in the recalculation of garnet analyses on the basis of 12 (0), provides another method of checking chemical analyses. Table 18 shows the analyses of 5-64 and 35-64 recalculated on the basis of 24 (0). In neither of these two cases is the 3 : 2 : 3 ratio in ideal agreement. Both show Si to be high and R^{+2}

to be low. The R^{+3} in 35-64 is in close agreement to the theoretical value, whereas that for 5-64 is high. The high SiO_2 in both specimens is undoubtedly due to inclusions not completely removed during the separation. More specifically this is probably the result of quartz impurities, since this is the major included mineral to be found in the garnets studied. The low R^{+2} and high R^{+3} values of 5-64 almost certainly arise from a low FeO determination, as shown above. The FeO of 35-64 probably closely agrees with the correct value, but still may be a little on the low side. The exact reason for the low R^{+2} in 35-64 is not altogether apparent to the writer.

It is interesting to note that an analysis by Crosby of a garnet from a schist in the staurolite zone, taken from an almost identical locality as 145-64, compares favourably with the chemical analysis and the physical parameters of the garnet collected and determined by the writer.

The use of Winchell's (1958) and Sriradamas's (1957) diagrams for the estimation of molecular composition of garnets from physical properties, was not undertaken. These diagrams adopt the values of the physical properties for garnet end-members mentioned above, and are constructed on the basis of the assumption that linearity exists in the physical properties between end-members. Estimations of molecular composition can be made in terms of three end-member components, or at the best four in the case of one of Winchell's diagrams. Such diagrams would have given only mere estimates of the accuracies of chemical analyses, and were consequently not used.

In summary, it is felt that of the chemical analyses made, probably only the values of FeO and Fe_2O_3 are subject to any notable error. These values are

Table 13. Partial chemical analyses, and molecular compositions of garnets from Kootenay Lake amphibolites

	12-63	25a-63	28c-63	5-64	35-64	65-64	77-64	86-64	92-6 4	94-64	109-64	119-64	167-64
Fe_2O_3	2.83	2.04	3.21	3.60	1.52	2.17	1.42	3.55	2.61	2.04	1.23	3.33	3.10
FeO	22.61	22.09	21.25	19.10	21.37	24.27	21.33	22.20	21.35	21.13	22.20	20.49	21.32
MnO	1.87	1.32	1.46	1.90	2.20	1.16	1.12	1.14	2.36	3.00	2.51	2.07	1.41
MgO	2.74	3.48	4.39	2.11	2.02	3.25	3.15	2.55	2.45	2.21	1.72	2.66	3.39
CaO	9.47	10.94	8.46	10.97	10.69	9.36	12.31	9.45	9.32	10.89	9.39	8.93	10.70

Analyst C.J. Dodds

Molecular composition

	12-63	25a-63	28c-63	5-64	35-64	65-64	77-64	86-64	92-64	94-64	109-64	119-64	167-64
Almandite	54.46	50.62	51.34	49.18	52.26	56.15	48.65	55.49	53.31	50.24	55.73	52.86	50.17
Spessartite	4.56	3.06	3.57	4.96	5.45	2.72	2.59	2.89	5.97	7.23	6.38	5.41	3.36
Pyrope	11.76	14.21	18.90	9.68	8.80	13.39	12.80	11.36	10.90	9.36	7.69	12.23	14.22
Grossularite	20.02	25.80	15.72	23.67	28.47	20.96	31.59	22.27	21.02	26.62	26.03	17.91	22.40
Andradite	9.20	6.31	10.47	12.51	5.02	6.78	4.37	7.99	8.80	6.55	4.17	11.59	9.85

Table 14. Physical parameters of garnets from Kootenay Lake amphibolites

I Index of refraction (N) at 25°C

	4-63	12-63	25a-63	28c-63	29a-63	5-64	35-64	65-64
Measured	1.798	1.796	1.789	1.794	1.794	1.795	1.793	1.795
Using Ford's data	-.---	1.800	1.791	1.797	-.---	1.802	1.794	1.800
Using Skinner's data	-.---	1.801	1.791	1.797	-.---	1.800	1.794	1.797

	77-64	86-64	92-64	94-64	109-64	119-64	167-64
Measured	1.785	1.794	1.792	1.791	1.795	1.796	1.792
Using Ford's data	1.786	1.798	1.801	1.795	1.796	1.804	1.796
Using Skinner's data	1.783	1.796	1.798	1.795	1.796	1.803	1.794

II Unit cell dimensions (a_o, Å) at 25°C

	4-63	12-63	25a-63	28c-63	29a-63	5-64	35-64	65-64
Measured	11.569	11.620	11.634	11.597	11.632	11.642	11.641	11.622
Using Skinner's data	--.---	11.635	11.636	11.621	--.---	11.665	11.644	11.623
a_o/N	6.434	6.470	6.503	6.464	6.483	6.486	6.492	6.475

	77-64	86-64	92-64	94-64	109-64	119-64	167-64
Measured	11.646	11.622	11.628	11.639	11.633	11.623	11.634
Using Skinner's data	11.645	11.634	11.637	11.646	11.633	11.640	11.642
a_o/N	6.520	6.478	6.488	6.499	6.481	6.474	6.492

Table 15. Partial chemical analyses and molecular compositions of garnets from schists and acid igneous veins; from Kootenay Lake.

Garnets from schists

	1-63	2-63	136a-64	145-64	152-64
Fe_2O_3	4.75	3.37	1.94	2.13	1.98
FeO	29.34	30.11	29.42	32.23	28.99
MnO	.34	.22	1.56	1.63	3.33
MgO	1.59	2.41	2.98	3.01	2.44
CaO	4.63	3.88	2.78	2.01	3.19

Analyst - C.J. Dodds

Garnets from acid veins

	5-63	22-63
Fe_2O_3	1.68	1.33
FeO	28.70	25.83
MnO	8.34	11.88
MgO	.65	.49
CaO	1.67	1.99

Analyst - C.J. Dodds

Molecular composition

	1-63	2-63	136a-64	145-64	152-64
Almandite	76.28	76.04	73.79	77.06	71.06
Spessartite	.90	.56	3.96	3.95	8.27
Pyrope	7.37	10.85	13.32	12.83	10.65
Grossularite	-.--	1.06	2.36	-.--	3.47
Andradite	15.45	11.49	6.57	6.16	6.55

Molecular composition

	5-63	22-63
Almandite	70.96	62.56
Spessartite	20.89	29.15
Pyrope	2.86	2.11
Grossularite	-.--	1.83
Andradite	5.29	4.35

Table 16. Physical parameters of garnets from schists and acid veins from Kootenay Lake

I Index of refraction (N) at 25°C

	1-63	2-63	3-63	31a-63	57-64	136a-64	145-64	152-64
Measured	1.807	1.806	1.797	1.813	1.802	1.808	1.809	1.809
Using Ford's data	1.819	1.820	-.---	-.---	-.---	1.814	1.813	1.814
Using Skinner's data	1.819	1.820	-.---	-.---	-.---	1.813	1.813	1.814

	5-63	22-63
Measured	1.817	1.816
Using Ford's data	1.822	1.820
Using Skinner's data	1.821	1.819

II Unit cell dimensions (a_o, Å) at 25°C

	1-63	2-63	3-63	31a-63	57-64	136a-64	145-64	152-64
Measured	11.567	11.560	11.563	11.546	11.603	11.550	11.548	11.560
Using Skinner's data	11.601	11.581	--.---	--.---	--.---	11.561	11.553	11.578
a_o/N	6.401	6.401	6.434	6.368	6.438	6.388	6.381	6.390

	5-63	22-63
Measured	11.562	11.587
Using Skinner's data	11.571	11.582
a_o/N	6.363	6.380

Table 17. Chemical analyses and physical parameters for two garnets from schists, Kootenay Lake after Crosby (1960)

	A	B
SiO_2	39.56	37.28
TiO_2	.26	.10
Al_2O_3	20.22	20.42
Fe_2O_3	1.32	1.63
FeO	32.33	30.96
MnO	1.61	1.51
MgO	2.46	2.85
CaO	1.90	4.42
Na_2O	- --	.10
K_2O	-.--	.07
H_2O^+	.77	.50
Total	100.43	99.84
N	1.808	1.793
a_o, Å	11.550	11.564
a_o/N	6.388	6.450

A. Garnet from the Ruth Formation (Staurolite zone) collected at the confluence of Leake and Coffee Creeks.

B. Garnet from the Plaid Lake Formation (sillimanite zone) collected near the head of Crawford Bay.

Table 18. Chemical and physical data for two garnets from Kootenay Lake amphibolites

PARTIAL WET CHEMICAL ANALYSES *

	5-64	35-64
SiO_2	40·90	40·52
TiO_2	0·40	0·57
Al_2O_3	21·11	21·02
Fe_2O_3	3·60	1.52
FeO	19·10	21.37
MnO	1·90	2·20
MgO	2·11	2·02
CaO	10·97	10·69
TOTAL	100·09	99·91

NUMBER OF IONS ON THE BASIS OF 24 (O)

	5-64		35-64	
Si	6.282	6·28	6·275	6·28
Al	------		------	
Al	3,821	4·28	3.837	4.08
Fe^{+3}	0 416		0·177	
Ti	0 046		0·066	
Mg	0·484	5 00	0·466	5·30
Fe^{+2}	2·458		2·768	
Mn	0·248		0·289	
Ca	1·810		1·774	

	FORMULAE
5-64	$\left(Fe^{+2}_{2\cdot46}\,Ca_{1\cdot81}\,Mg_{0\cdot48}\,Mn_{0\cdot25}\right)_{5\cdot00}\left(Al_{3\cdot82}\,Fe^{+3}_{0\cdot42}\,Ti_{0\cdot05}\right)_{4\cdot28}\,Si_{6\cdot28}\,O_{24}$
35-64	$\left(Fe^{+2}_{2\cdot77}\,Ca_{1\cdot77}\,Mg_{0\cdot47}\,Mn_{0\cdot29}\right)_{5\cdot30}\left(Al_{3\cdot84}\,Fe^{+3}_{0\cdot18}\,Ti_{0\cdot07}\right)_{4\cdot08}\,Si_{6\cdot28}\,O_{24}$

	N	a_0(Å)
5-64	1·795	11·642
35-64	1·793	11·641

MOLECULAR COMPOSITION	5-64	35-64
ALMANDITE	49.18	52·26
SPESSARTITE	4·96	5 45
PYROPE	9·68	8·80
GROSSULARITE	23·67	28·47
ANDRADITE	12·51	5.02

* Analyst : A. Stelmach

probably variably low in the case of FeO, and as a consequence variably high in the case of Fe_2O_3. Any errors resulting from chemical analyses may be partly apparent in discrepancies existing between calculated and directly determined physical parameters. Bias in chemical analysis arising from included minerals is undoubtedly more difficult to discern. Minute granules of quartz, although the most common inclusions, will obviously not affect the analyses of interest. Of those generally minor inclusions that occur, sphene may give rise to slight errors in the CaO content. In view of the colour similarity of sphene and garnet, its final separation by hand picking is difficult. The remaining minor inclusions, such as plagioclase, opaque ores, biotite, and chlorite, are generally present in trivial amounts, and consequently, are not considered to constitute any serious bias to chemical analyses.

DISCUSSION OF RESULTS

COMPOSITION OF GARNETS

Garnets from the central Kootenay Lake amphibolites are notably calcium-rich pyralspites, being predominantly composed of the almandite and grossularite molecules, with smaller but somewhat comparable amounts of pyrope and andradite. The spessartite molecule is on the whole insignificant. The average molecular composition of these garnets compares reasonably with the average of Wright (1938) and Troger (1959), Table 19. A plot of the major end-member molecules, after Wright, is illustrated in Fig. 11, for comparison with the Kootenay Lake garnets from amphibolites. It is interesting to note that Troger (p. 17) was unsuccessful in attempting to distinguish between the composition of garnets from ortho and para-amphibolites.

Figure 11. Compositional range of garnets from amphibolites (after Wright, 1938).

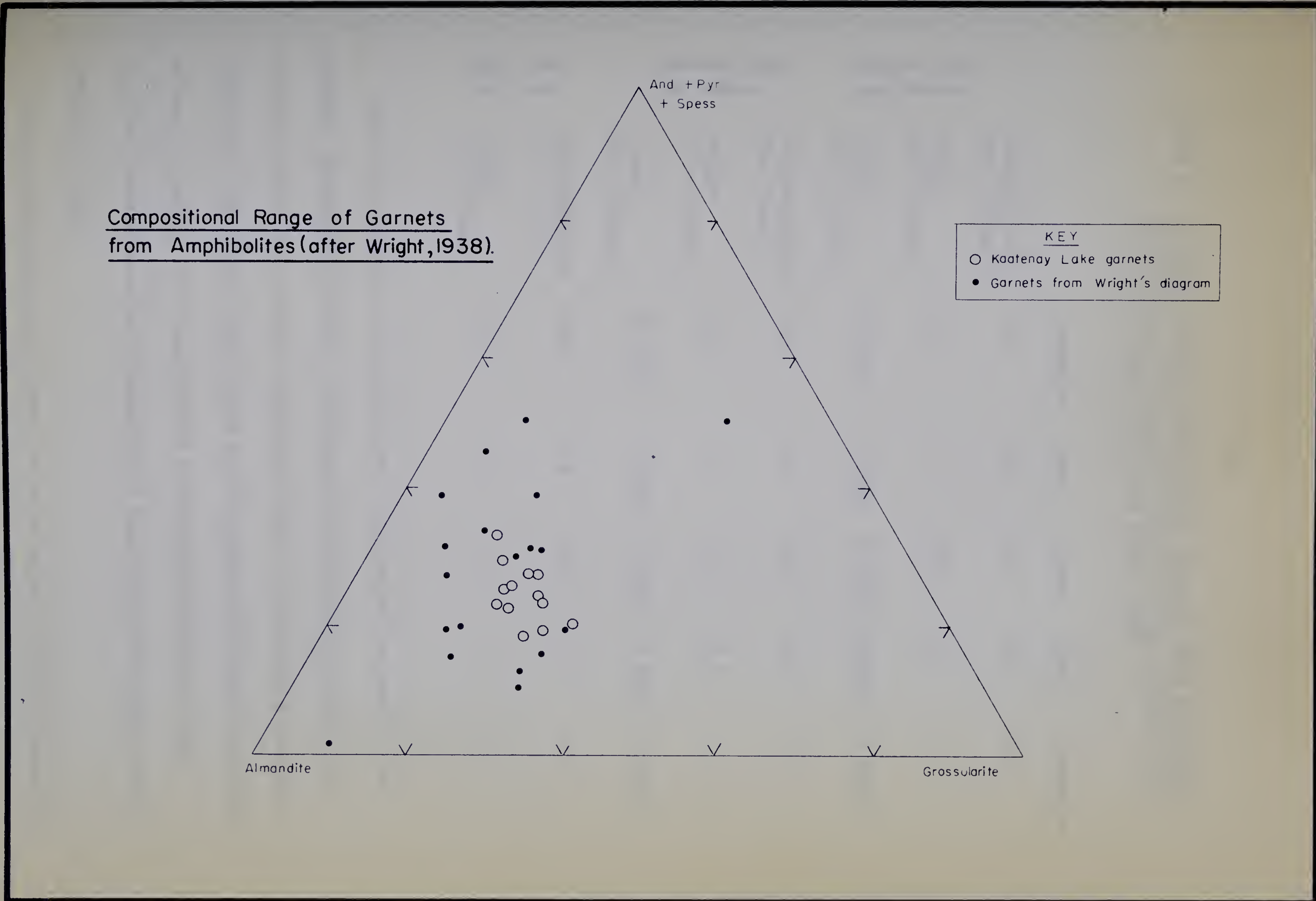

Compositional Range of Garnets
from Amphibolites (after Wright, 1938).
And + Pyr
+ Spess
KEY
Kaatenay Lake garnets
Garnets from Wright's diagram
Almandite
Grossularite

Figure II.

Table 19. Average molecular composition of Kootenay Lake garnets from amphibolites, schists, and acid igneous veins, compared to the averages of Wright (1938), and Troger (1959)

		Almandite	Spess.	Pyrope	Gross.	Andradite
Garnets from amphibolites	Kootenay Lake (Av. 13 anal.)	52.3	4.5	11.9	23.3	8.0
	Wright (Av. 20 anal.)	53.6	-.-	20.3	20.7	-.-
	Troger (Av. 21 anal.)	54.0(±6)	3.5(±3)	16.5(±4)	20.0(±5)	6.0(±4)
Garnets from bt. schists	Kootenay Lake (Av. 5 anal.)	74.8	3.5	11.0	1.4	9.3
	Wright (Av. 23 anal.)	73.0	-.-	13.4	6.0	-.-
	Troger (Av. 33 anal.)	73.0(±9)	3.0(±2)	17.5(±9)	4.0(±3)	2.5(±3)
Gnt. from ign. vein	Kootenay Lake (Av. 2 anal.)	66.8	25.0	2.5	.9	4.8
	Wright (Av. 35 anal.)	41.8	47.1	-.-	-.-	-.-

Garnets from schists consist predominantly of the almandite molecule, with subsidiary pyrope and andradite. The spessartite and grossularite molecules are generally insignificant, except for specimen 152-64. The Kootenay garnets from schists are, on the whole, slightly richer in the almandite and andradite molecules, but poorer in pyrope, when compared with the averages of Wright and Troger. Fig. 12A illustrates the range of composition of these garnets with respect to those compiled by Wright.

The two garnets from the acid igneous veins are typically almandite, spessartite

Figure 12. Compositional range of garnets from (A) schists and (B) pegmatites and granites (after Wright, 1938).

Compositional Range of Garnets from (A) Schists and (B) Pegmatites and Granites. (after Wright, 1938).

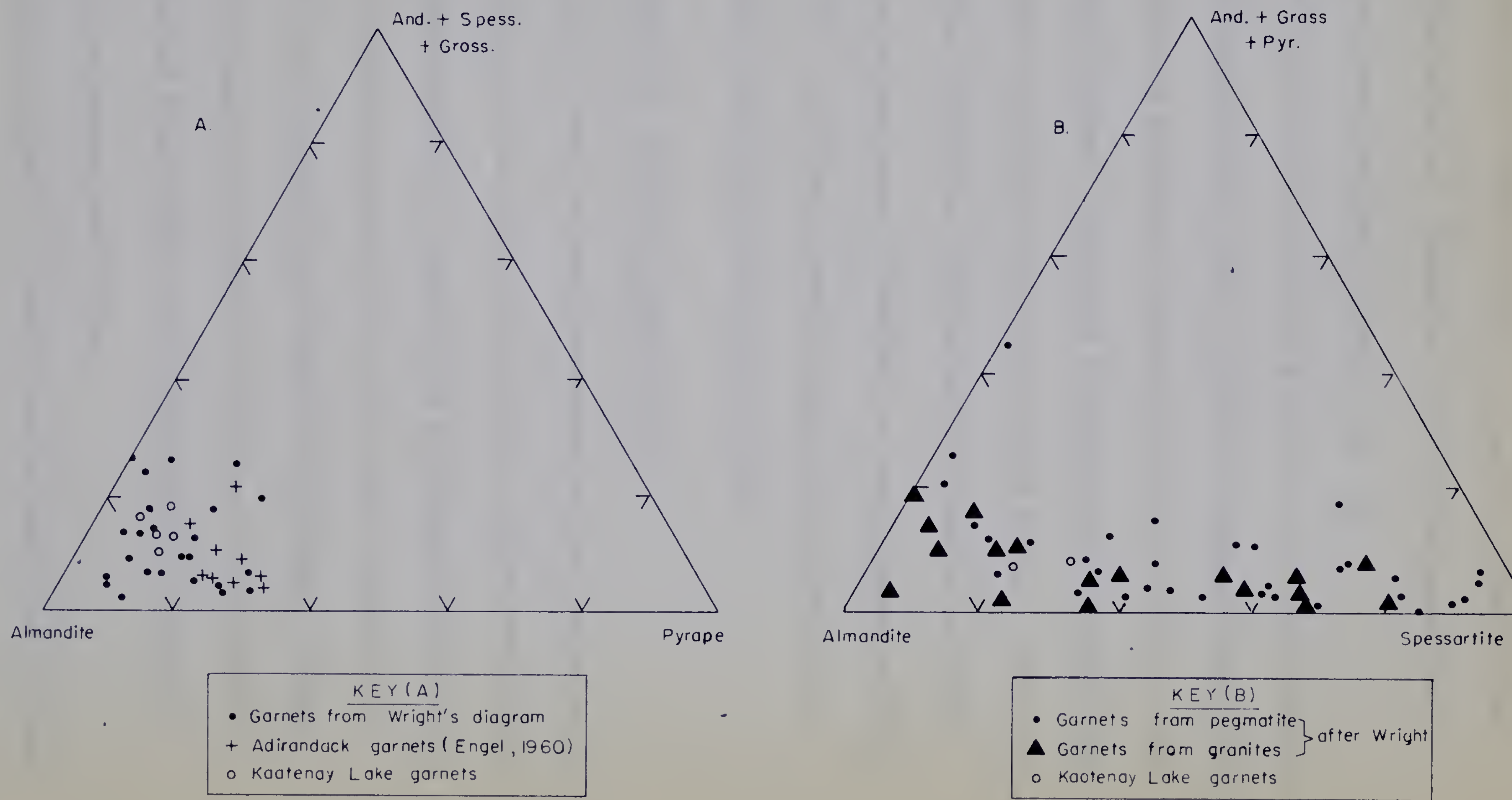


Figure 12.

rich, but when compared with Wright's average, are poorer in spessartite and richer in the almandine molecules. Comparison is made of the composition of these two garnets, with those recorded in literature Fig. 12B.

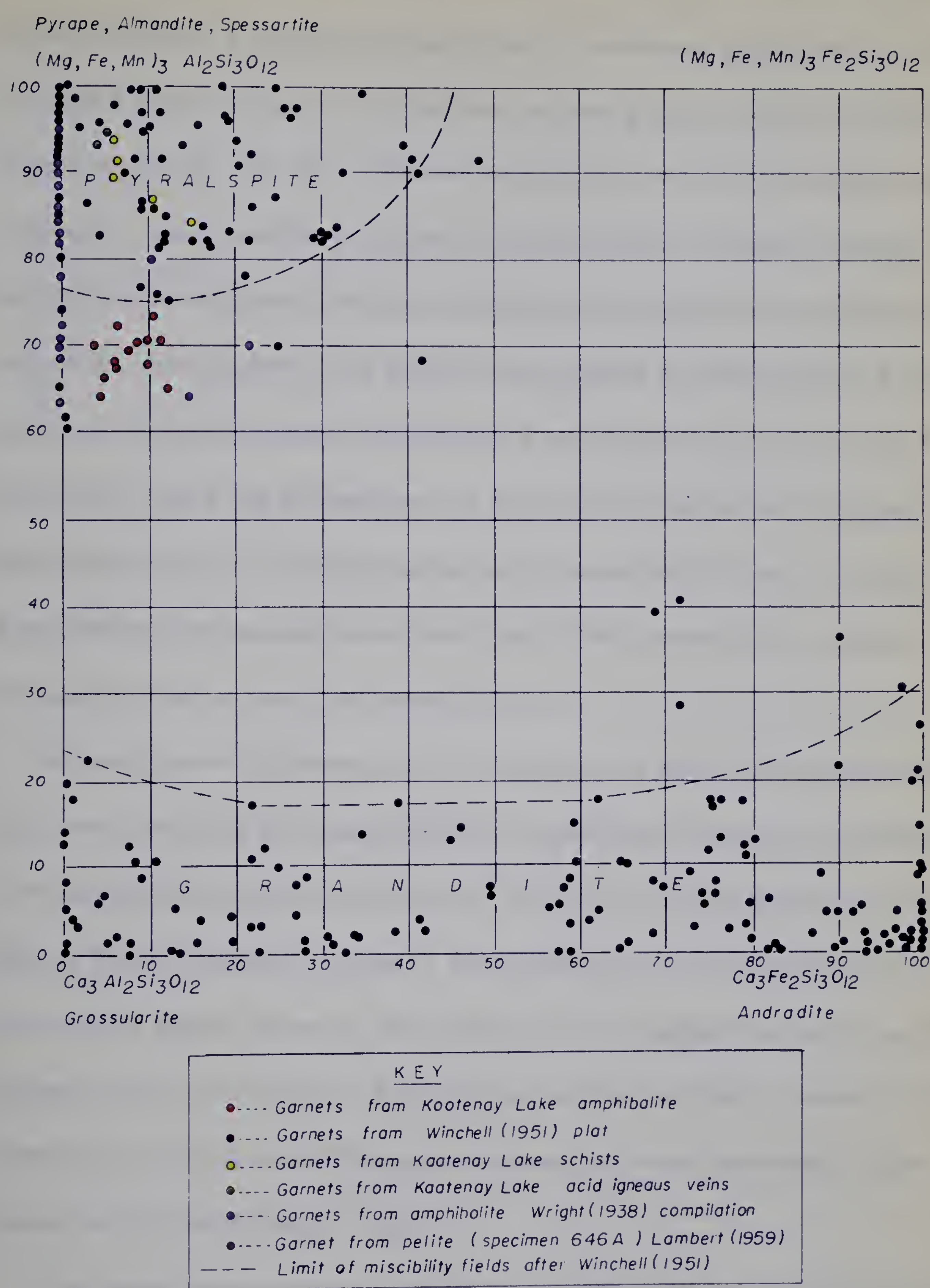
Due to the relatively high CaO content of garnets from the central Kootenay Lake amphibolites, these garnets plot (Fig. 13) within the supposed "immiscibility gap" between grandites and pyralspites on Winchell's (1951, Fig. 377, p. 484) compositional variation diagram. This appears to indicate that Winchell's limits for the "solubility field" of pyralspites should be extended further. Of the twenty analyses of garnets from amphibolites collected from the literature by Wright, eight plot outside the limits proposed by Winchell, for the pyralspite "solubility field". Lambert (1959, p. 567) has recorded an analysis for a garnet from a pelite, which also plots outside Winchell's proposed limits.

VARIATIONAL TRENDS IN GARNET COMPOSITION

Variational trends have been indicated from several relatively recent studies in the composition of garnets from schists with progressive regional metamorphism. Miyashiro (1953), demonstrated that in garnets from the Gosaisyo-Takanuki area in Japan, there is a significant decrease in the MnO content coupled with an increase in the FeO content during prograde regional metamorphism. Lambert (1959) has illustrated a progressive decrease in CaO and an increase in (FeO + MgO), whereas Engel and Engel (1960) noted increased MgO and decreased Fe_2O_3 and MnO with progressive grade change.

Miyashiro (p. 202) has suggested a crystallo-chemical explanation for these progressive regional metamorphic changes in garnet composition, based on the

Figure 13. Variational composition diagram, for garnets including the central Kootenay Lake garnet analyses.



Pyrope, Almandite, Spessartite
(Mg, Fe, Mn)3 Al2Si3O12
(Mg, Fe, Mn)3 Fe2Si3O12
P Y R A L S P I T E
G R A N D I T E
Ca3 Al2Si3O12
Grossularite
Ca3Fe2Si3O12
Andradite
KEY
Garnets from Kootenay Lake amphibolite
Garnets from Winchell (1951) plot
Garnets from Kootenay Lake schists
Garnets from Kootenay Lake acid igneous veins
Garnets from amphibolite Wright (1938) compilation
Garnet from pelite (specimen 646A) Lambert (1959)
Limit of miscibility fields after Winchell (1951)

Figure 13.

structural model of garnet proposed by Menzer (1928). Menzer demonstrated that garnet consists of a relatively large unit cell, containing eight formula units, in which the silicon-oxygen tetrahedra form isolated groups linked to octahedra of trivalent ions (Al, Fe, Cr). Divalent ions (Fe, Ca, Mn, Mg), in eight fold co-ordination, are interstitially situated within the silicon-aluminum network. It is particularly notable that divalent metal ions are in eight fold co-ordination. Miyashiro contends that of the divalent ions capable of substitution in the garnet structure, Mn has the greatest facility on a radius ratio basis toward eight fold co-ordination; hence the predominance of the spessartite molecule in garnets of low metamorphic grade. With progressive grade change (both P and T increase), those smaller ions less apt to combine in eight fold co-ordination, become increasingly free to enter the garnet structure.

Although certain differences in composition were found in the garnets from the central Kootenay Lake amphibolites, no significant sympathetic trends similar to those described above were observed. This fact is not too surprising on the basis of Crosby's isograds, eleven of these garnets are of similar (sillimanite zone) metamorphic grade. However, the remaining two (supposedly occurring within the garnet zone, according to their position relative to Crosby's isograds), show essentially no significant differences in composition when compared to those garnets within the sillimanite zone.

If all seven garnet analyses from schists (including the two presented by Crosby) are viewed in the light of progressive increase of metamorphic grade (on the basis of Crosby's isograds) no significant trends are apparent. It should be recollected here that the metamorphic change involved is one from supposed staurolite grade

to sillimanite grade.

Sturt (1962, p. 185) constructed a diagram plotting (CaO + MnO) versus (FeO + MgO) for all garnet analyses from schists available in the literature. From this he demonstrated a progressive decline in the (CaO + MnO) values with a concomitant increase in the (FeO + MgO) values, with prograde metamorphism. Although there is a certain overlapping of the fields of garnet composition in terms of these parameters, the trend appears to be significant. When the Kootenay Lake garnets from schists are plotted on this diagram (Fig. 14), they agree reasonably well with Sturt's hypothesis. Plots of all garnets from amphibolites are also included in this diagram. A notable difference in the compositional field of predominantly sillimanite grade garnets from amphibolites is observed, when a comparison is made with the field for garnets from schists of a similar metamorphic grade. Although a slight compositional trend is discernable from this diagram, its exact significance is somewhat questionable, since two garnet specimens (5-64 and 65-64) both considered to be within the garnet zone (on the grounds of Crosby's isograds), plot at either extremity.

Sturt (p. 188) demonstrated that there is a linear relationship between the CaO content and the ratio a_o/N for the garnets from schists in the Dalradian of Scotland. Fig. 15 shows a similar relationship to that found by Sturt, for all garnets analysed from the Kootenay Lake area. Sturt further adopted this ratio as an indicator of metamorphic grade. There is a progressive decline in the value of a_o/N ratio (and consequently a decrease in the CaO content) in garnets collected from schists to the north of the Grey Creek Stock, as this granitic body is approached. The trend involves specimens B (after Crosby), 3-63, 1-63, 2-63 and 31a-63. The

Figure 14. A plot of ($CaO + MnO$) versus ($FeO + MgO$) for Kootenay Lake garnets from schists and amphibolites (modified after Sturt, 1962).

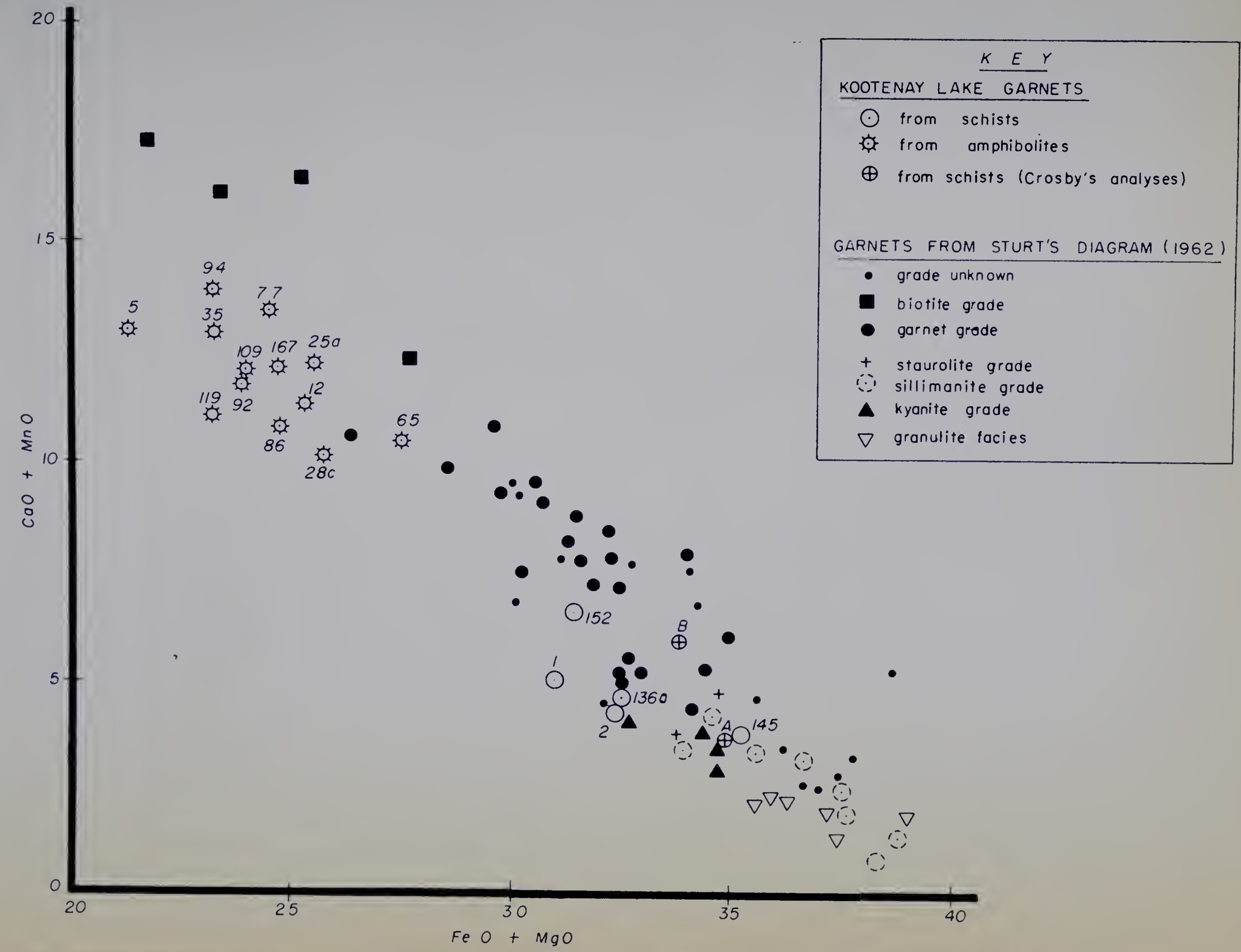
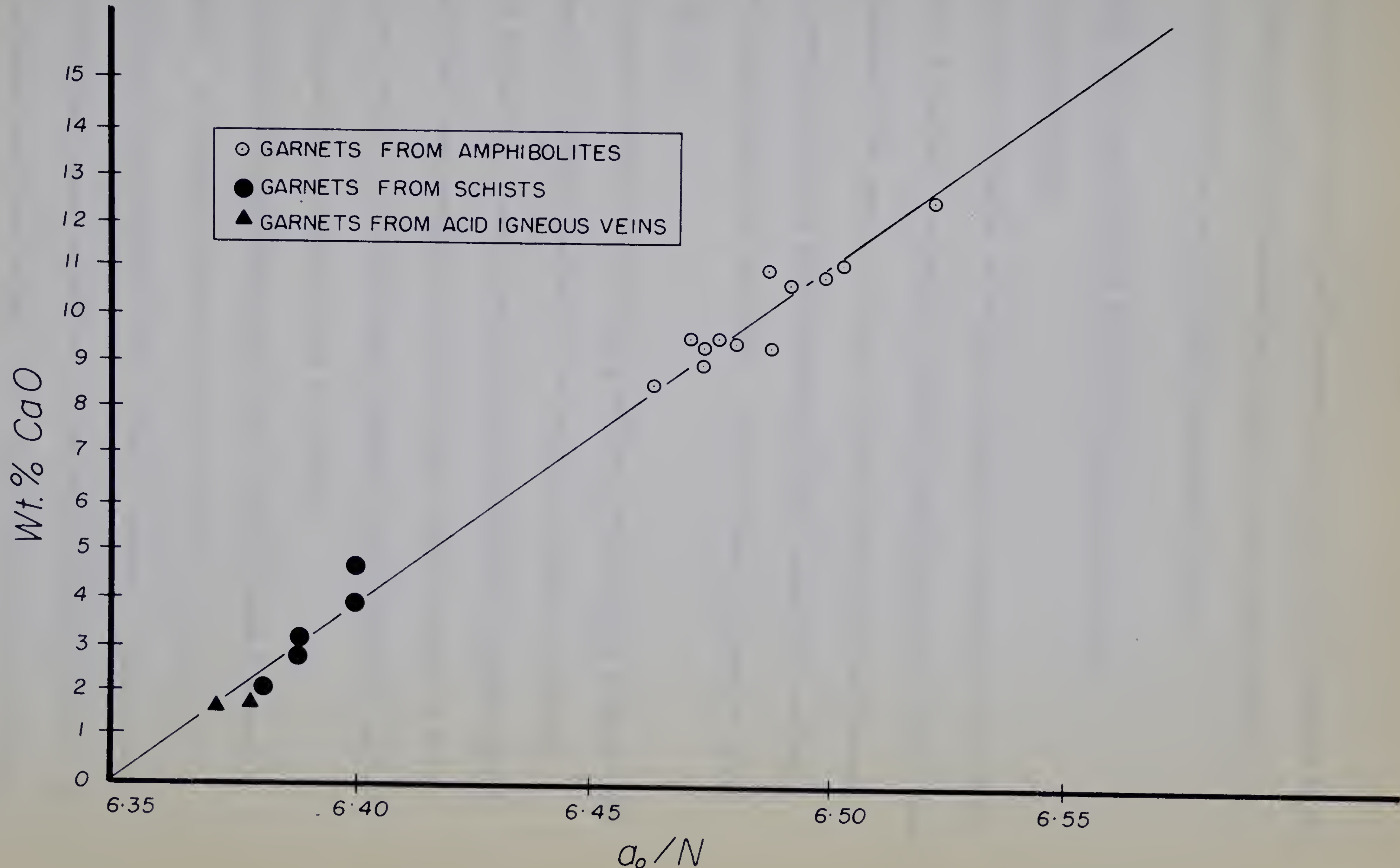

K E Y
KOOTENAY LAKE GARNETS
from schists
from amphibolites
from schists (Crosby's analyses)
GARNETS FROM STURT'S DIAGRAM (1962)
grade unknown
biotite grade
garnet grade
staurolite grade
sillimanite grade
kyanite grade
granulite facies
CaO + MnO
FeO + MgO
0
5
10
15
20
25
30
35
40
5
94
35
77
109
167
25a
119
92
12
86
28c
65
152
1
B
136a
2
A
145

Figure 14

Figure 15. A plot of a_o/N versus CaO wt. per cent for garnets from amphibolites, schists, and acid igneous veins.



GARNETS FROM AMPHIBOLITES
GARNETS FROM SCHISTS
GARNETS FROM ACID IGNEOUS VEINS
Wt.% CaO
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
6·35
6·40
6·45
6·50
6·55
a_o/N

Figure 15.

significance of such a trend is again uncertain since it is not fully apparent to the writer whether the garnets developed as a result of contact metamorphism, or if they are "relicts" from the earlier regional metamorphic phase.

THE EFFECTS OF VARIATION IN BULK ROCK COMPOSITION ON GARNET COMPOSITION

To the writer's knowledge, no serious consideration has been given toward the evaluation of the effects of variation in bulk rock composition on the compositional changes apparent in the garnets. A series of simple diagrams were constructed, plotting increasing content of each constituent of garnet composition available, against the corresponding bulk rock value. Several of these diagrams are illustrated in Fig. 16.

With increased content of FeO, Fe_2O_3 and total iron as Fe_2O_3 in garnet from schists, there is no systematic pattern in the corresponding bulk rock content. However, a progressive increase in the CaO and MnO contents of garnets arises irrespective of bulk rock composition, which remains almost invariable in both cases (Fig. 16A and B). The MgO content appears to vary somewhat sympathetically with increased MgO in the bulk rock (Fig. 16C).

The garnets from the amphibolites again show interesting trends in respect to CaO and MnO. An increase in the MnO content occurs with essentially no change in the composition of the bulk rock. There is, however, a vaguely sympathetic trend between garnet and bulk rock in the case of the CaO content. No systematic variations were found in MgO, FeO, Fe_2O_3, and total iron as Fe_2O_3.

The values of CaO, FeO, MgO (the major constituents of garnet composition

Figure 16. Plots illustrating the influence of bulk composition of host rocks on progressive increase in certain constituents of garnet composition. (Plots A, B, C concern garnetiferous schists, while those of D and E concern garnetiferous amphibolites.

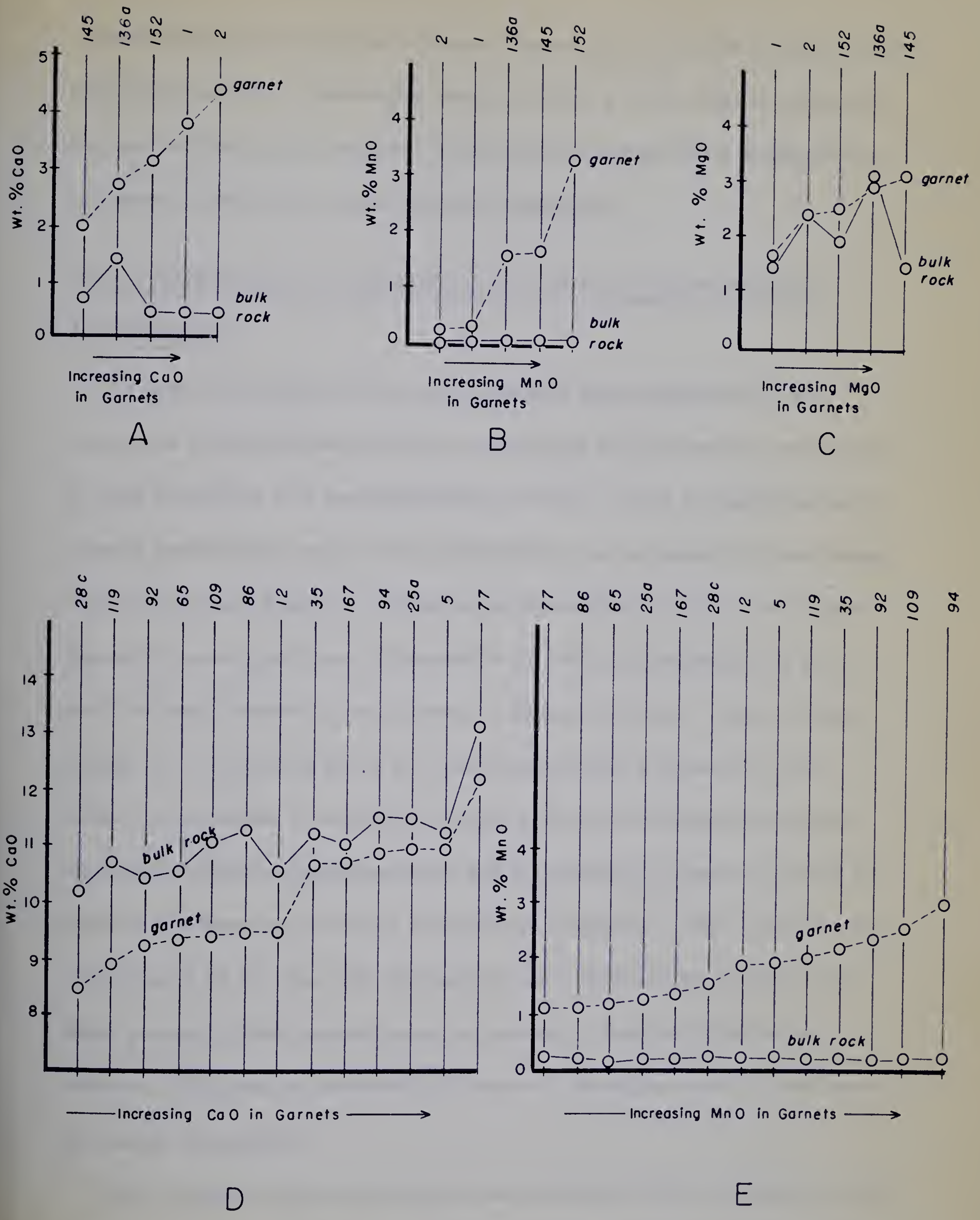

145
136a
152
1
2
Wt. % CaO
garnet
bulk rock
Increasing CaO in Garnets
A
2
1
136a
145
152
Wt. % MnO
garnet
bulk rock
Increasing MnO in Garnets
B
1
2
152
136a
145
Wt. % MgO
garnet
bulk rock
Increasing MgO in Garnets
C
28c
119
92
65
109
86
12
35
167
94
25a
5
77
Wt. % CaO
bulk rock
garnet
Increasing CaO in Garnets
D
77
86
65
25a
167
28c
12
5
119
35
92
109
94
Wt. % MnO
garnet
bulk rock
Increasing MnO in Garnets
E

Figure 16.

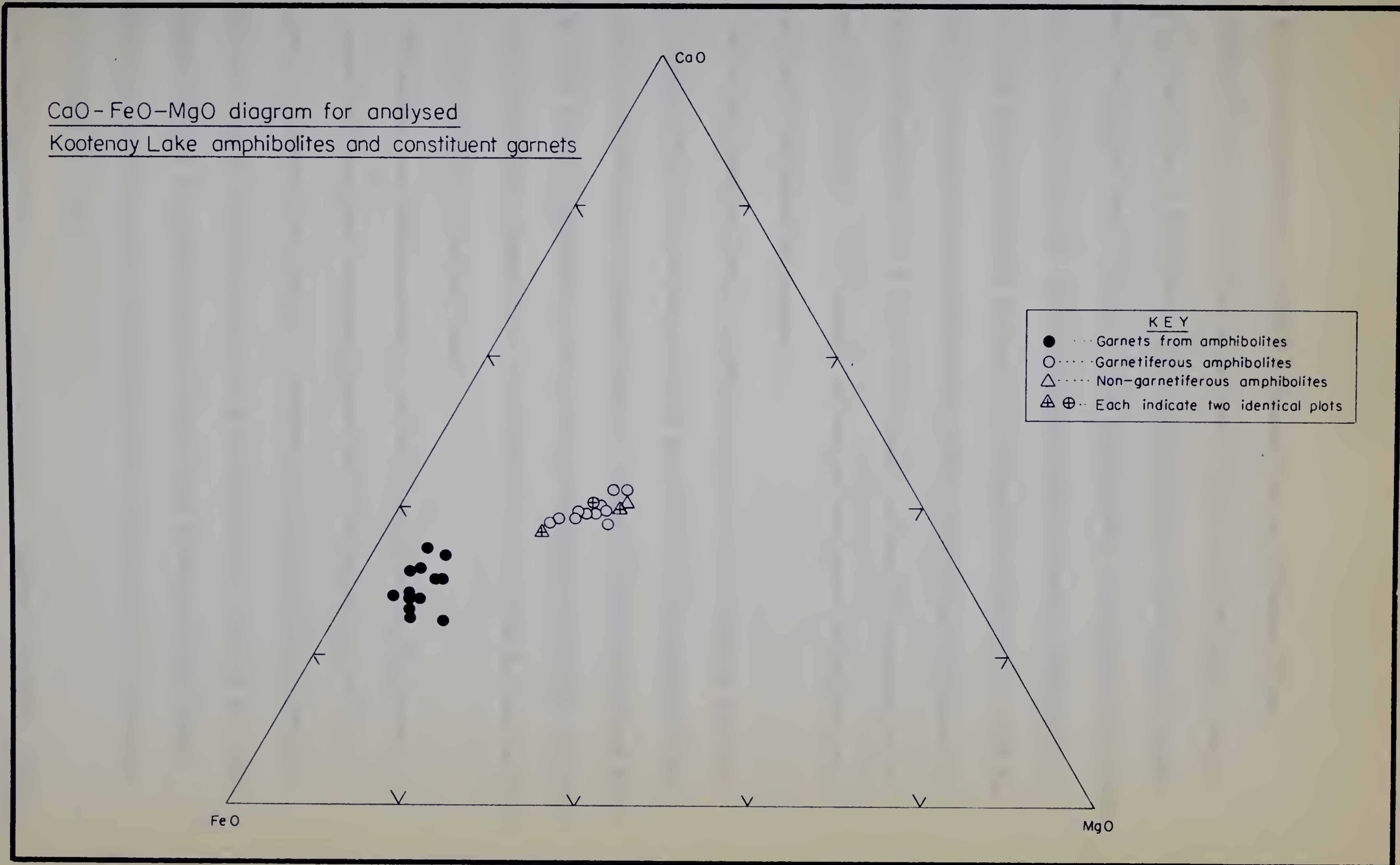
in amphibolites) were plotted on a ternary diagram Fig. 17 for both the garnets and amphibolite bulk rock. Although a trend indicating a slight variation essentially between FeO and MgO is apparent in the bulk rock compositions, the garnets do not appear to reflect any similar change in composition.

THE COEXISTENCE OF GARNETIFEROUS AND NON-GARNETIFEROUS AMPHIBOLITES

An interesting feature of the central Kootenay Lake amphibolites is the occurrence of garnetiferous varieties (containing up to 13 volume per cent garnet) in close association with non-garnetiferous varieties. Since no substantial metamorphic grade change appears to be involved (this can be stated with some degree of certainty where these two varieties occur almost side by side), it would seem logical to suspect significant differences in the bulk rock composition to be the decisive factor determining the presence or absence of garnet. Engel and Engel (1962a, p. 73) postulate both T and P and compositional differences for the production of garnets in amphibolites from the Northwest Adirondack Mountains. De Waard (1965) also has demonstrated that the presence or absence of garnet is a function of differences existing in the bulk rock composition. This, however, does not appear to be the case with the Kootenay Lake amphibolites, for as has been shown previously, the composition and mineralogy of these amphibolites are strikingly similar and no substantial differences in the major chemical constituents are readily discernable.

Slight chemical and somewhat greater mineralogical differences appear to exist between two amphibolites, one garnetiferous (5-64) and the other non-garnetiferous

Figure 17. CaO-FeO-MgO diagram for analysed Kootenay Lake amphibolites and constituent garnets.



CaO-FeO-MgO diagram for analysed
Kootenay Lake amphibolites and constituent garnets
CaO
FeO
MgO
KEY
Garnets from amphibolites
Garnetiferous amphibolites
Non-garnetiferous amphibolites
Each indicate two identical plots

Figure 17.

(4-64) occurring about one hundred yards apart in Tam O'Shanter Creek. Specimen 5-64 is notably higher in FeO and Na_2O, but surprisingly lower in Al_2O_3, and lower in MgO than 4-64. Mineralogically, 5-64 contains significantly less plagioclase (11.7% to 19.2%) and also has a notably lower An content (An38 to An57) than 4-64. Both contain essentially the same modal amount of hornblende (approximately 70 per cent). The significant difference in both the amount and composition of plagioclase may partly demonstrate a difference in the mode of partitioning in this particular phase, and partially account for the appearance of garnet. Unfortunately no chemical analyses of hornblende were determined to complete the picture.

The writer is aware of only one detailed account in the literature dealing with the problem of the coexistence of both garnetiferous and non-garnetiferous amphibolites at the same metamorphic grade. Wiseman (1934) has described this relationship from the epidiorites of the Southwest Highlands of Scotland, and has analysed the bulk rock composition, hornblendes and garnet from the two varieties occurring just within the garnet isograd.

Differences were found to occur in the FeO, Na_2O and Al_2O_3 contents, the garnetiferous specimen contained greater FeO, but less Na_2O and Al_2O_3 than the non-garnetiferous specimen. Wiseman concluded that the significant dissimilarity lies in the FeO content, since the differences in alumina and soda are explainable in the greater amount of plagioclase in the non-garnetiferous specimen. These findings are remarkably similar to those noted above between specimens 5-64 and 4-64.

Hornblende analyses are very similar in both rocks studied by Wiseman, but

slight differences are discernable. These comprise richer soda, slightly richer FeO, and poorer MgO in the garnet-bearing rock, as opposed to that of the non-garnet-bearing rock. The Al_2O_3 content of both minerals is essentially the same.

Wiseman (p. 390) has indicated the possibility of a reaction whereby garnet could conceivably be produced at the garnet isograd in rocks of basic composition. He states as follows:

> "It may be tentatively suggested that after the hornblende has attained a certain composition largely by reaction with chlorite and iron ore, any excess chlorite may commence to react with the plagioclase and iron ore to produce garnet. Soda and quartz would be liberated, and it is reasonable to infer that this soda has entered the hornblende molecule."

The complication of the reaction producing garnet in basic assemblages, can be further exemplified if the distribution of alumina is examined in the reactions occurring at or within the garnet isograd. Both Wiseman and Miyashiro (1958) have noted a substantial change in the alumina and alkali content of "calciferous" amphiboles in the transition between the biotite and garnet zones. The change is essentially from non-aluminous actinolite to hornblende. A further reaction commonly takes place within the garnet zone involving the redistribution of alumina. This reaction occurs between epidote and albite, with the development of a more anorthite-rich plagioclase. Thus for production of garnet to occur, it would probably have to "compete" with both the above mentioned reactions for alumina. It might be suggested that the development of a more anorthite-rich plagioclase may have been retarded somewhat owing to the formation of garnet. This would account for the substantially lower An content of plagioclase in the garnetiferous amphibolite.

The reaction(s) initially triggering the nucleation of garnet would appear complex,

and may conceivably be the result of slight differences in chemical composition. Mention was made above to the slight differences existing in the bulk rock FeO contents between garnetiferous and non-garnetiferous amphibolites from the Kootenay Lake and southwest Highland epidiorite examples. In both cases, the garnetiferous amphibolites contained a slightly greater FeO content. It is interesting to note that Jones and Galway (1964, p. 81) have illustrated rather strikingly a direct relationship existing between the "free ferrous oxide" and the amount of garnet which is formed. It may, however, be said with some degree of certainty, that neither substantial chemical compositional differences nor T and P change seem to be the cause of the appearance or non-appearance of garnet in the amphibolites examined in the Kootenay Lake area.

FEATURES INFERRING INSTABILITY IN THE GARNETS

A commonly occurring feature exhibited by the garnets from the central Kootenay Lake amphibolites is the peripheral development of felsic-rich rims or selvages. It would appear from petrographic evidence that these selvages are not the result of the partial formation of garnet, but almost undoubtedly represent the partial breakdown of this mineral. However, the question arising as to whether this breakdown is the result of prograde or retrograde metamorphic change, is somewhat more difficult to answer.

As was previously mentioned, all stages of the decomposition of garnet are to be found from thin peripheral selvages developed about only partially corroded garnet porphyroblasts to the complete removal of any vestiges of garnet. Any explanation as to the direction of the reaction (ie. prograde or retrograde) must

take into consideration the almost invariable production of randomly oriented biotite flakes within the garnet-felsic milieu, the dominant production of plagioclase over quartz and the minor development of pale bluish green hornblende generally associated with the pale bluish green tinged borders developing marginally about the "matrix" hornblende grains.

Reaction rims occurring about garnets are moderately well documented in literature. Examples having an apparently superficial resemblance to those from the Kootenay Lake amphibolites have been described by Oliver (1956) from lavas, intrusive rocks, and ignimbrites in the English Lake District; by Edwards (1936) in rhyodacites from Victoria; and by Brammal and Bracewell (1933) from the Dartmoor Granite. There is probably, however, little or no genetic significance to be attached to these similarities. Two particularly interesting metamorphic examples have been described, one from eclogite facies rocks by Alderman (1936), and another from the uppermost almandine-amphibolite facies by de Waard (1965).

In describing the occurrence of garnet in the granulite-facies terrane within the Adirondacks Highlands, de Waard mentions the development of corona textures about garnets in the uppermost almandine-amphibolite facies. The breakdown reaction according to de Waard is clearly one producing orthopyroxene and anorthite-rich plagioclase. The reaction occurs by way of the following equation (de Waard, eq. 5, p. 167):

$$NaCa_2(Fe,Mg)_4\,Al_3Si_6O_{22}(OH)_2 + (Fe,Mg)_3\,Al_2Si_3O_{12} + 5\,SiO_2$$

hornblende almandite quartz

$$\rightleftarrows 7(Fe,Mg)\,SiO_3 + NaAlSi_3O_8 + 2CaAl_2Si_2O_8 + H_2O.$$

orthopyroxene plagioclase

This reaction is the result of progressive metamorphism, where P_{H_2O} decreases (dehydration) or T increases, and has been used by Buddington (1963) to delineate the orthopyroxene isograd in the Adirondacks. It is significant to note that de Waard describes the relative instabilities of both biotite and hornblende to be characteristic of the transition from the almandine-amphibolite facies to the hornblende granulite facies.

Alderman (1936, p. 515), has described the retrograde breakdown of garnet in eclogites from Glenelg to produce hornblende alone, but more commonly plagioclase, hornblende and opaque ore. These minerals outline symplectitic rings about the corroded garnet, the innermost is composed dominantly of plagioclase with a few flakes of bluish-green hornblende, whereas the outermost is comprised of bluish-green hornblende alone. In comparatively rare instances, Alderman noted the production of brown biotite associated with the decomposition of the garnet.

Alderman's observations bear a remarkable resemblance to those made by the writer concerning the breakdown of the garnets from the Kootenay Lake amphibolites. The latter garnet alteration rims do, however, notably lack well developed outer rims of bluish-green hornblende (although vague outer zones of this coloured mineral have been observed in the odd case), and invariably carry orange brown

biotite.

In view of the considered instability of biotite and hornblende in basic assemblages undergoing progressive metamorphism in the upper almandine-amphibolite facies, and the complete lack of orthopyroxene in association with the breakdown of garnet, it is tentatively suggested that the change resulting in the decomposition of garnet is one involving retrograde metamorphism, rather than prograde. Coupled with this, is the observed green colouration of brown hornblende grains of the "matrix" which is considered by Engel and Engel (1962a, p. 59) to be possibly a retrograde feature. Whatever the nature and degree of this retrograde change, the production of minor amounts of biotite and to some extent that of secondary hornblende, must have required the introduction of small quantities of potash and soda. Also, the reaction involved must almost certainly have been one of thermal change alone, in view of the generally complete randomness of the breakdown products. A possible mechanism giving rise to the decomposition may have been that of the invasion of acid igneous material that intensely pervades the rocks of the central high grade belt. This could conceivably account for the introduction of "hydrous" rich fluids, containing potash and soda, which in turn may have triggered decomposition of the garnets. This, of course, is merely a suggested mechanism for the breakdown of garnet. Whether this is the result of igneous activity occurring immediately after the apical stage of regional metamorphism (involving part of the Kootenay Lake Intrusive phase) or due to some later event such as the intrusion of the "satellitic" granite bodies (ie. the Nelson Intrusive phase), would obviously prove difficult to assess without considerably more detailed work.

Undoubted retrograde metamorphism has affected certain gernetiferous schists from the Ruth Formation (ie. samples 136a-64 and 145-64) to produce thin somewhat discontinuous envelopes of chlorite flakes and occasional white mica about marginally corroded garnet porphyroblasts. This could well be associated with the late stage deformation which resulted in the cataclasis of parts of the peripheral zones of the Nelson Batholith.

The effects of probable upgrading due to the imprinting of contact upon regional metamorphism are visible in the textures to be found in specimen 31a-63. The reaction appears to have been one involving the production of fibrolite at the expense of biotite which envelopes corroded garnet "fragments".

CHAPTER V

CONCLUSIONS

Neither evidence which fully corroborates nor evidence which completely refutes Crosby's proposed pattern of metamorphic zones was found by the writer. Of the many thin sections of pelitic rock types examined, only two were found to contain minerals diagnostic of grade of metamorphism. Evidence from the amphibolites proved to be equally fruitless. As a consequence, the picture envisaged by Crosby, for the metamorphic history of the central Kootenay Lake area, was adopted in its entirety for the purposes of this study.

The amphibolites, both garnetiferous and non-garnetiferous, examined in detail, proved remarkably similar in their gross chemistry, mineralogy and texture (albeit with the exception of the presence or absence of garnet). Comparisons of these rocks with those of basic igneous parentage by means of the C.I.P.W. norm indicated that the central Kootenay Lake amphibolites are most like normal tholeiitic basalts and dolerites. The amphibolites also compare well with the compositions of amphibolites from other regions. Of the possible origins that might be considered for these rocks, the writer tends to favour the suggestion that they represent metamorphosed equivalents of basic igneous rocks, conceivably relatable to the Kaslo volcanics as has been pointed out by Crosby. Obviously more chemical work, particularly on the trace elements (especially Ni, Cr and Co), would be required in order to either substantiate or disprove this proposed origin.

The schists were found to be somewhat more variable in composition and

mineralogy and probably represent metamorphosed semipelitic rocks.

Garnets from amphibolites proved to be calcium rich pyralspites predominantly composed of the almandite and grossularite molecules. Garnets from schists, on the other hand, were found to be remarkably almandite rich with subsidiary amounts of pyrope and andradite, whereas those from the acid igneous veins were typically composed of the almandite and spessartite molecules. All compared well with the molecular compositional averages recorded in the literature for garnets of their particular host rock type. It is notable that in all cases, the garnets from the central Kootenay Lake amphibolites plot within the supposed "immiscibility gap" between grandites and pyralspites on Winchell's diagram. Nine other analyses documented in the literature also plotted outside the limits proposed by Winchell. This indicates that Winchell's "solubility field" for pyralspite garnets should be extended further.

Although variational trends involving essentially a decrease in CaO, MnO, and Fe_2O_3, and an increase in MgO and FeO with progressive increase in grade of regional metamorphism, are well documented in the literature for garnets from pelitic rocks, no such systematic trends were discernable in the garnets from the central Kootenay Lake area. In spite of slight differences existing in the composition of the garnets, both from the schists and the amphibolites, no trends relatable to change in metamorphic grade were found.

When the Kootenay Lake garnets from schists were plotted on Sturt's diagram of (CaO + MnO) versus (FeO + MgO), these garnets were found to approximately fall into the "grade fields" outlined. Plots of all garnets from amphibolites were also included in this diagram. A notable difference in the composition fields of

predominantly sillimanite grade garnets from amphibolites is observed, when comparison is made with the field of garnet from schists of a similar metamorphic grade.

A similar linear relationship to that found by Sturt between the CaO content and the ratio a_o/N of garnets, was also demonstrated for those garnets occurring in the central Kootenay Lake area, irrespective of the host rock types. This would seem to verify Sturt's use of this ratio as an indicator of the CaO content in garnets.

The effects of the difference in bulk rock composition on garnet composition was briefly reviewed. A series of simple diagrams were constructed, plotting a progressive increase in each constituent of garnet composition against the corresponding bulk rock values. In both garnets from schists and amphibolites with increased FeO, Fe_2O_3, and total iron as Fe_2O_3, no systematic increase in the bulk rock values were observed. However, the CaO and MnO content of garnets from schists and the MnO content of those from amphibolites were found to increase irrespective of the bulk rock values, which remained essentially constant. The values of MgO in garnets from schists and the CaO in those from amphibolites were found to vary somewhat sympathetically with an increase in the bulk rock values.

The coexistence of garnetiferous and non-garnetiferous amphibolites was briefly discussed. In view of the strikingly similar compositions of both varieties of amphibolites, coupled with their generally close association, it was felt that neither substantial chemical composition differences nor T and P change are to be attributed to the appearance or non-appearance of garnet in the amphibolites

examined. The reaction(s) initially triggering the nucleation of garnet would undoubtedly appear to be complex, but may partly stem from slight differences occurring in bulk rock composition, perhaps coupled with differences in the mode of partitioning of the chemical constituents between the various mineral phases. There is obvious need for a more complete study of the compositions of all mineral phases present in both varieties of amphibolites before a more comprehensive picture can be obtained concerning this problem. Unfortunately this was beyond the scope of the present study.

Features indicating instability in the garnets from both amphibolites and schists were observed. Undoubted retrograde metamorphism has affected certain of the garnets from schists, particularly those from the Ruth Formation. This has resulted in the peripheral development of chlorite and minor white mica at the expense of garnet. The garnets from amphibolites were found to exhibit all stages of decomposition from thin peripheral selvages developed about only partly corroded garnet porphyroblasts, to the complete removal of all vestiges of garnet. The writer tends to favour some form of retrograde change causing the breakdown of the garnet in view of the development of secondary hornblende and biotite. A tentatively suggested mechanism giving rise to this decomposition may have been that of the invasion of acid igneous material. This igneous material intensely pervades and in many cases exhibits cross-cutting relationships to the metamorphosed rocks. This could conceivably account for the introduction of "hydrous rich" fluids, containing potash and soda, which in turn may have triggered the decomposition of the garnets with the subsequent formation of plagioclase, biotite and minor secondary hornblende. Whether the introduction of these "hydrous rich"

fluids took place immediately after the apical stage of the regional metamorphism producing the garnets, or was due to some later event such as the intrusion of Crosby's post-tectonic granites, would obviously be difficult to assess without further detailed work.

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APPENDIX A

X-RAY FLUORESCENCE ANALYSIS

SAMPLE PREPARATION, OPERATING CONDITIONS, CHEMICAL ANALYSES OF STANDARDS, CALIBRATION CURVES, AND PRECISION AND DETECTABILITY DETERMINATIONS

APPENDIX A

Pulverisation of bulk rock samples was accomplished by means of a tungsten carbide lined "swing-mill". Undiluted samples (ie. no addition of cellulose), were "homogenised" by agitation for ten minutes in a Pica blender. All samples were then "briquetted" in an Applied Research Laboratories Inc. Briquetting machine, type 4451, for one minute at 30,000 p.s.i. Each had been backed and rimmed with cellulose powder for strength.

Analytical determinations were made using the Philips Norelco X-ray Fluorescence equipment (unit type 12215/0). Complete operating conditions are presented in Table 20.

The conversion of counts per second to weight per cent was accomplished by means of conventional calibration curves, derived from wet chemically analysed standards. The analyses of all standards used are presented in Table 21, whereas all calibration curves employed are presented in Figures 18 to 24.

The precision error of each element was determined from a series of measurements made on an appropriate standard (for example, 28c-63), following every three unknowns. Variations observed were treated statistically, employing the standard deviation function. Precision is expressed as a percentage and determined from:

$$\text{Precision } \% = \frac{1\ \text{S.D.}\ (\text{Peak value} - \text{Background value})}{\text{mean}\ \ (\text{Peak value} - \text{Background value})} \times 100$$

where (S.D.) standard deviation = $\sqrt{\dfrac{(m - x)^2}{(n - 1)}}$ m is mean value,
x is a value, and
n is the number of values taken.

The detectability for each element was also determined. This was computed as follows:

$$\text{Detectability \%} = 3 \text{ S.D. (Background value)} \times \frac{\text{Wt. \% Standard}}{\text{(Peak - Background)}}$$

It should be noted that 99.17% of all points are included between x - 3 S.D. and x + 3 S.D. (ie. 3 S.D.).

Table 22 includes the statistically determined values of precision and detectability for all elements analysed by X-ray fluorescence means.

Table 20 Operating conditions for X-ray fluorescence analysis

ELEMENT	'TARGET'	PEAK (°2θ)	B.G. (°2θ)	F.T. (sec.)	XTAL	CTR	CTRV	X-RP	PHA	PHLV	PHW
Mg	Cr	106.54	105.58	20	ADP	F.P.	1630	Vacuum	Diff.	10.5	12.0
Al	Cr	112.45	111.50	10	EDDT	F.P.	1640	Vacuum	Diff.	12.5	14.0
Si	Cr	77.80	77.10	10	EDDT	F.P.	1560	Vacuum	Diff.	7.0	6.2
Ca	W	14.85	14.00	10	EDDT	F.P.	1510	Vacuum	Diff.	7.5	8.0
Ti	W	86.22	85.00	10	LiF	F.P.	1485	Air	Diff.	6.5	7.5
Mn	W	62.95	61.60	20	LiF	F.P.	1470	Air	Diff.	7.0	13.0
Fe	Mo	57.55	56.75	10	LiF	Sc.	940	Air	Int.	1.5	-.-

<u>Explanation of Abbreviations:</u>

'Target' - Target tube; 50KV and 40 MA supplied to both W and Mo tubes; 50KV and 30MA to the Cr tube.

B.G. - Background position in °2θ

F.T. - Fixed Time used in counting

XTAL - Analysing Crystal

ADP - Ammonium Dihydrogen Phosphate

EDDT - Ethylene-Diamine-d-Tartrate

LiF - Lithium Fluoride

CTR - Counter (X-ray detector)

F.P. - Flow Proportional Counter (gas flow - 10% Methane, 90% Argon).

Sc. - Scintillation Counter

CTRV - Counter Voltage

X-RP - X-ray Path

PHA - Pulse Height Analyser

PHLV - Pulse Height Level Voltage

PHW - Pulse Height Width Voltage

Diff. - Differential (PHW engaged)

Int. - Integral (PHW disengaged)

Table 21 Chemical analyses used as X-ray fluorescence standards

	G.1	W.1	63-603-2	28c-63	I.R.5	KCCN-98	R-20	R-39	85736
SiO_2	72.48	52.55	69.30	50.93	50.81	56.99	48.06	46.14	54.43
TiO_2	.26	1.08	.04	1.49	.90	.94	2.20	3.63	1.36
Al_2O_3	14.20	14.98	15.20	15.32	13.82	16.47	15.29	15.36	19.80
Fe_2O_3	.78	1.41		1.32	.73	3.12	1.37	4.08	3.60
FeO	.97	8.71	.39	10.23	11.02	2.81	11.82	10.69	4.73
MnO	.03	.16	.03	.23	.20	.18	.19	.22	.09
MgO	.37	6.59	.41	7.05	8.11	1.13	4.71	4.26	2.19
CaO	1.35	10.98	1.33	10.21	9.38	3.19	6.56	6.89	2.22
Na_2O	3.29	2.14	1.88	.78	1.67	3.70	3.00	3.06	1.20
K_2O	5.52	.62	9.75	.96	.63	8.18	1.66	1.86	6.93
P_2O_5	.08	.12	.66	.19	.16	.23	.54	.70	.19
H_2O^-	.04	.14		.04	.05	.20	.14	.25	.90
H_2O^+	.26	.45	.30	1.40	2.44	1.81	3.33	2.24	2.50
Others - CO_2+ BaO+SrO+RbO F+S; Less O=S&F	.29	.10	--.--	--.--	.15	.87	.93	.38	--.--
Total	99.89	100.05	99.29	100.15	100.07	99.82	99.80	99.76	100.27

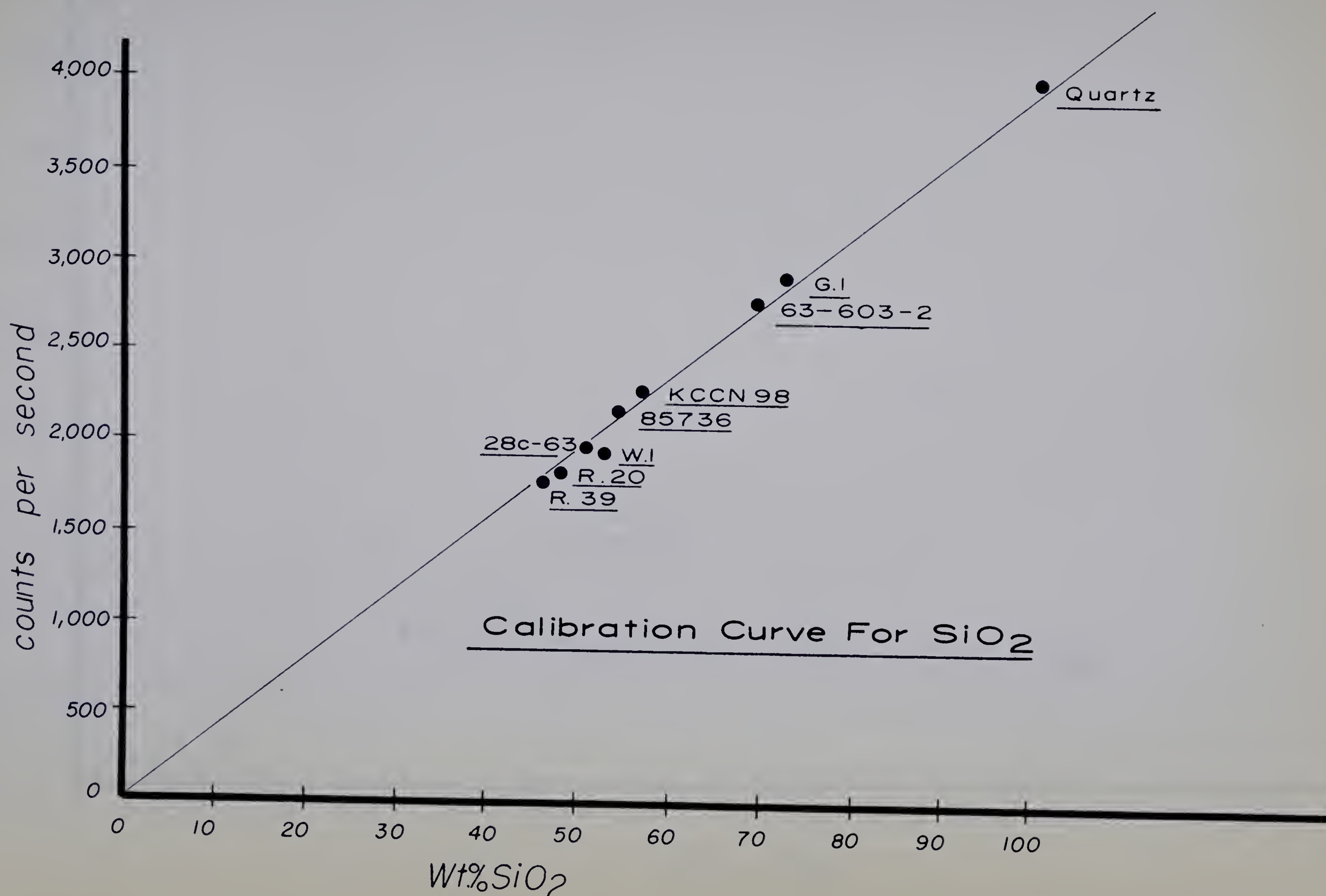
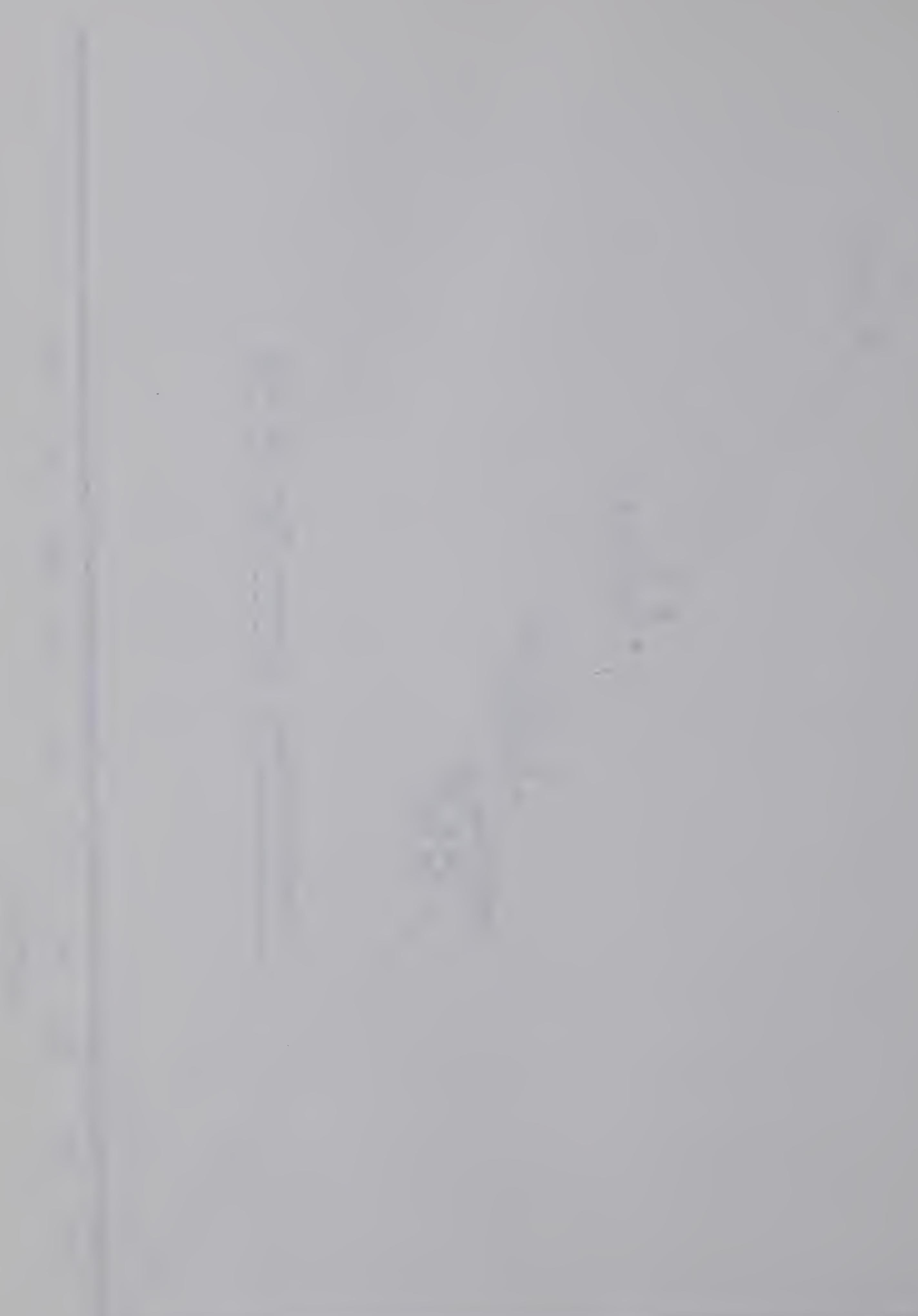

Calibration Curve For SiO_2
counts per second
Wt.% SiO_2
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
0
10
20
30
40
50
60
70
80
90
100
Quartz
G.I
63-603-2
KCCN 98
85736
28c-63
W.I
R.20
R. 39

Figure 18.



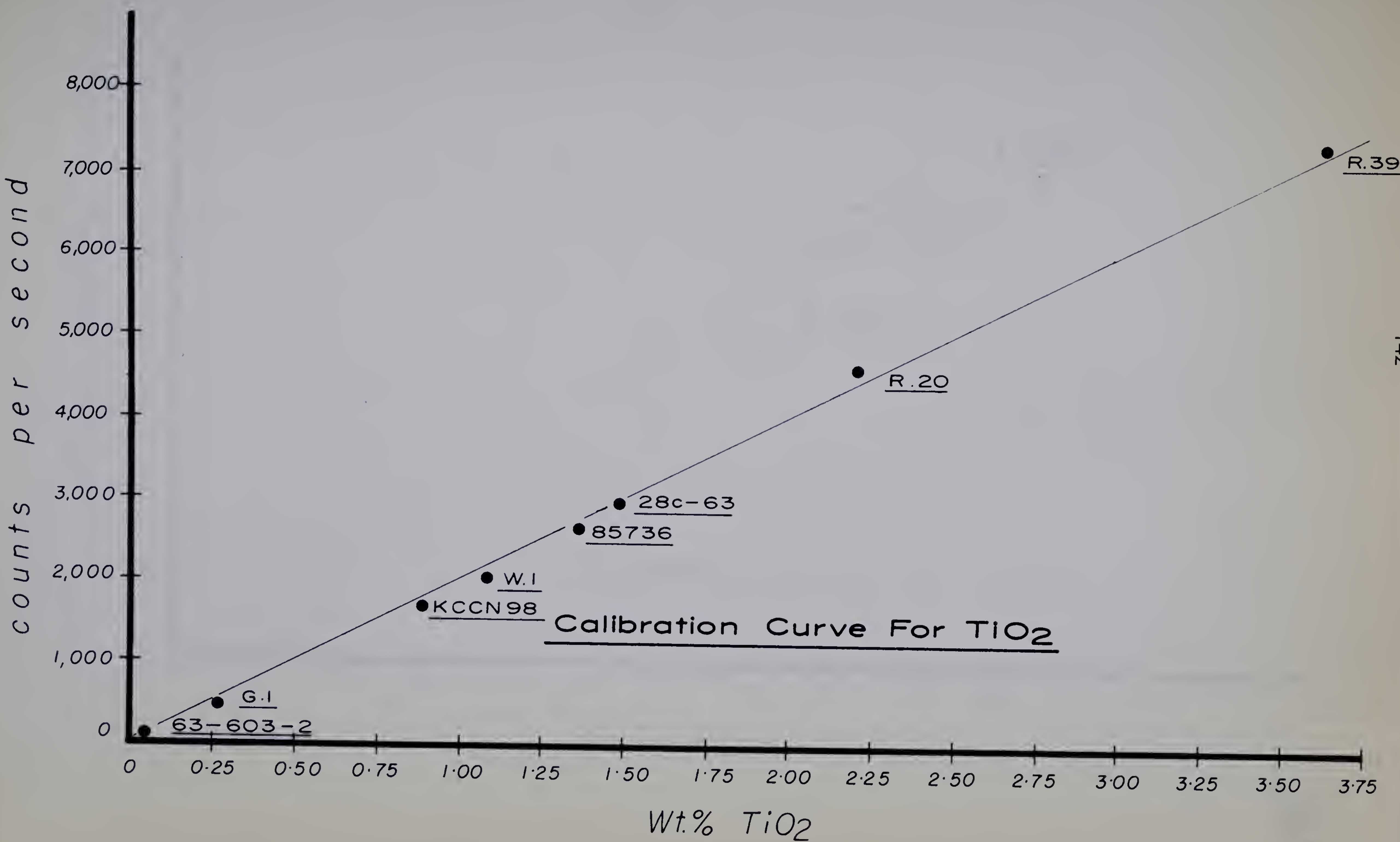
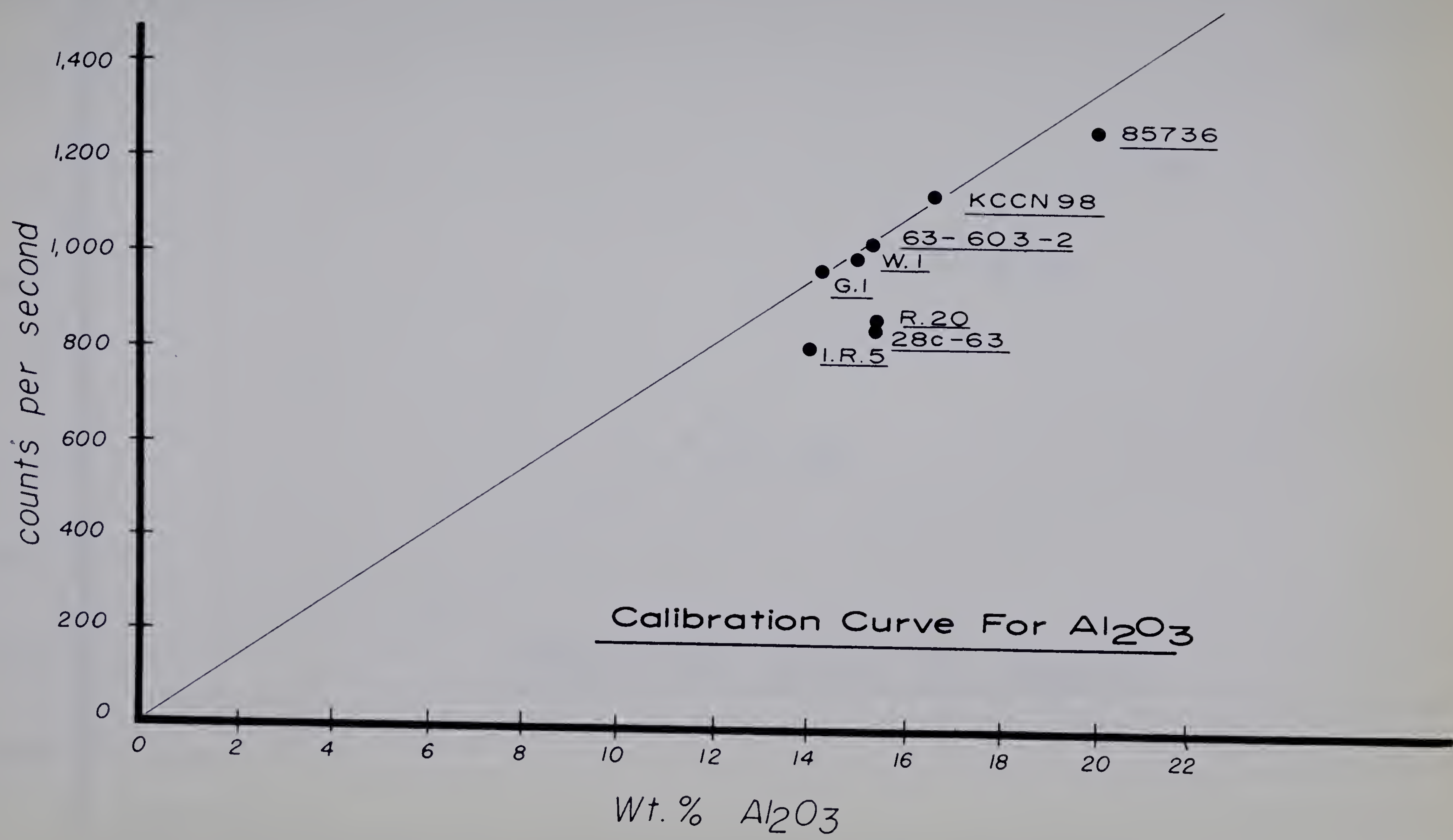
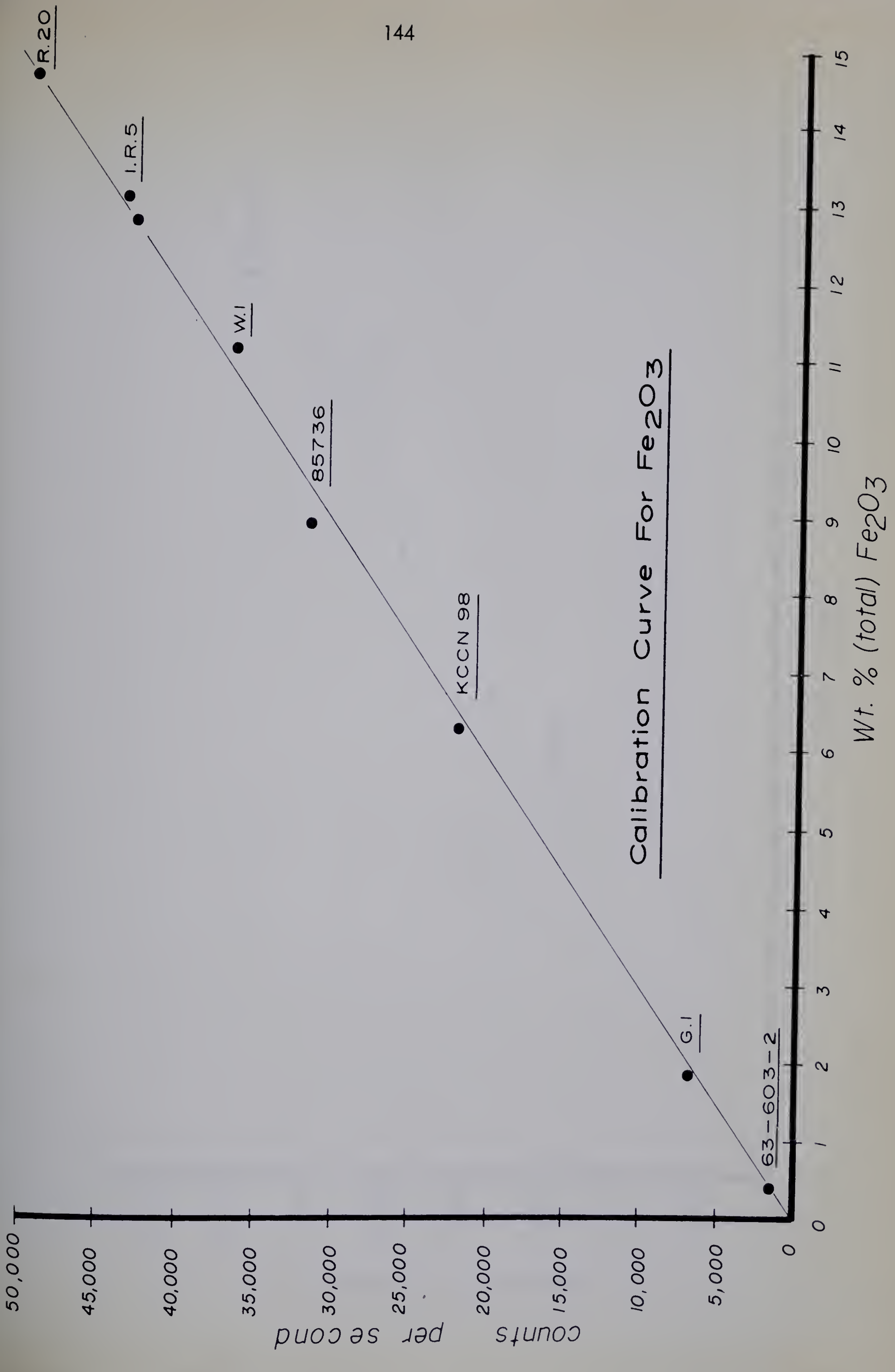

Calibration Curve For TiO2
counts per second
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
0·25
0·50
0·75
1·00
1·25
1·50
1·75
2·00
2·25
2·50
2·75
3·00
3·25
3·50
3·75
Wt.% TiO2
R.39
R.20
28c-63
85736
W.1
KCCN98
G.1
63-603-2

Figure 19.



1,400
1,200
1,000
800
600
400
200
0
counts per second
0
2
4
6
8
10
12
14
16
18
20
22
Wt. % Al2O3
85736
KCCN 98
63- 603 -2
W. I
G. I
R. 20
28c-63
I. R. 5
Calibration Curve For Al2O3

Figure 20.


Calibration Curve For Fe_2O_3
counts per second
Wt. % (total) Fe_2O_3
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5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
63-603-2
G.1
KCCN 98
85736
W.1
I.R.5
R.20

Figure 21.

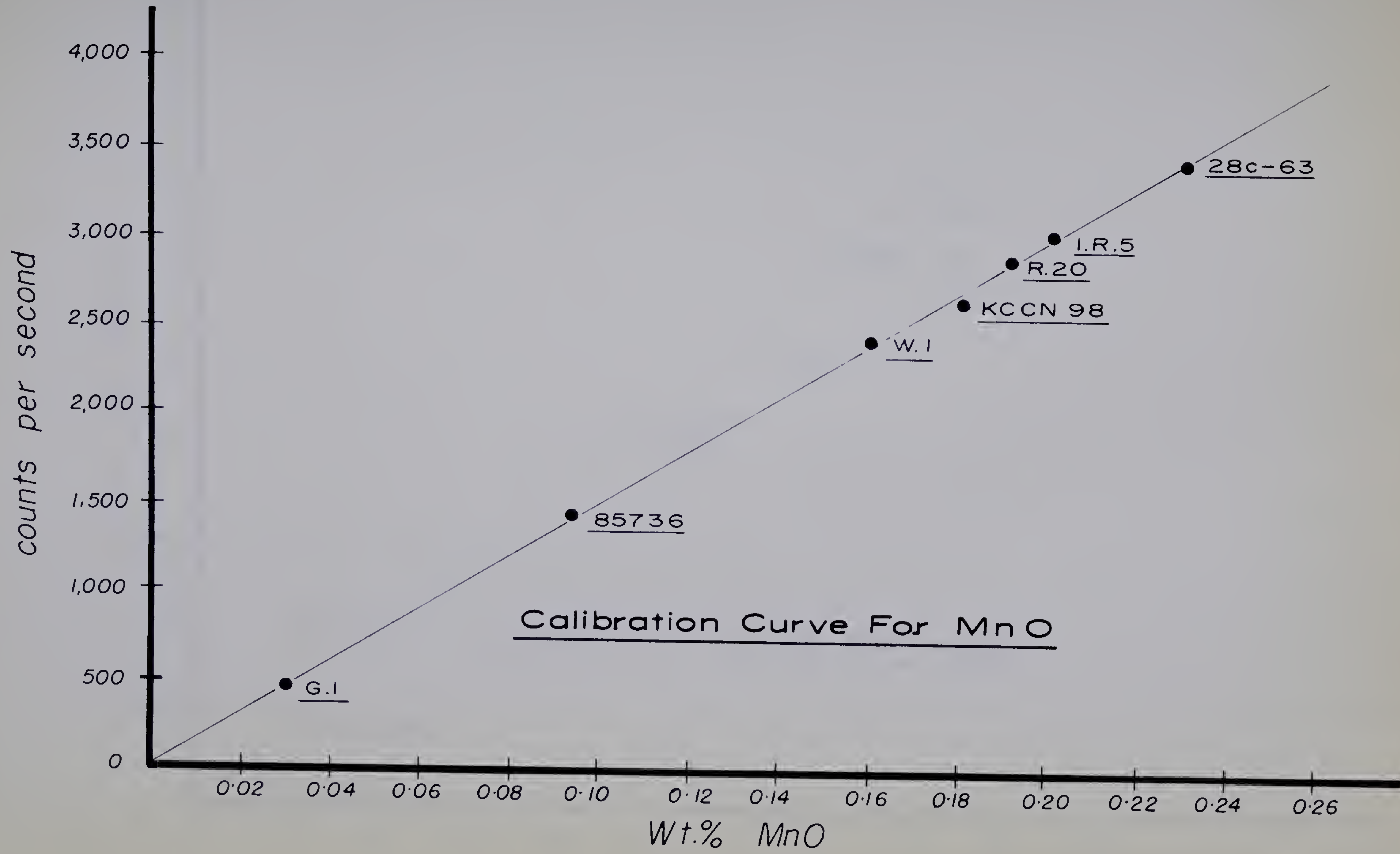
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
counts per second
28c-63
I.R.5
R.20
KCCN 98
W.I
85736
G.I
Calibration Curve For MnO
0·02
0·04
0·06
0·08
0·10
0·12
0·14
0·16
0·18
0·20
0·22
0·24
0·26
Wt.% MnO

Figure 22.

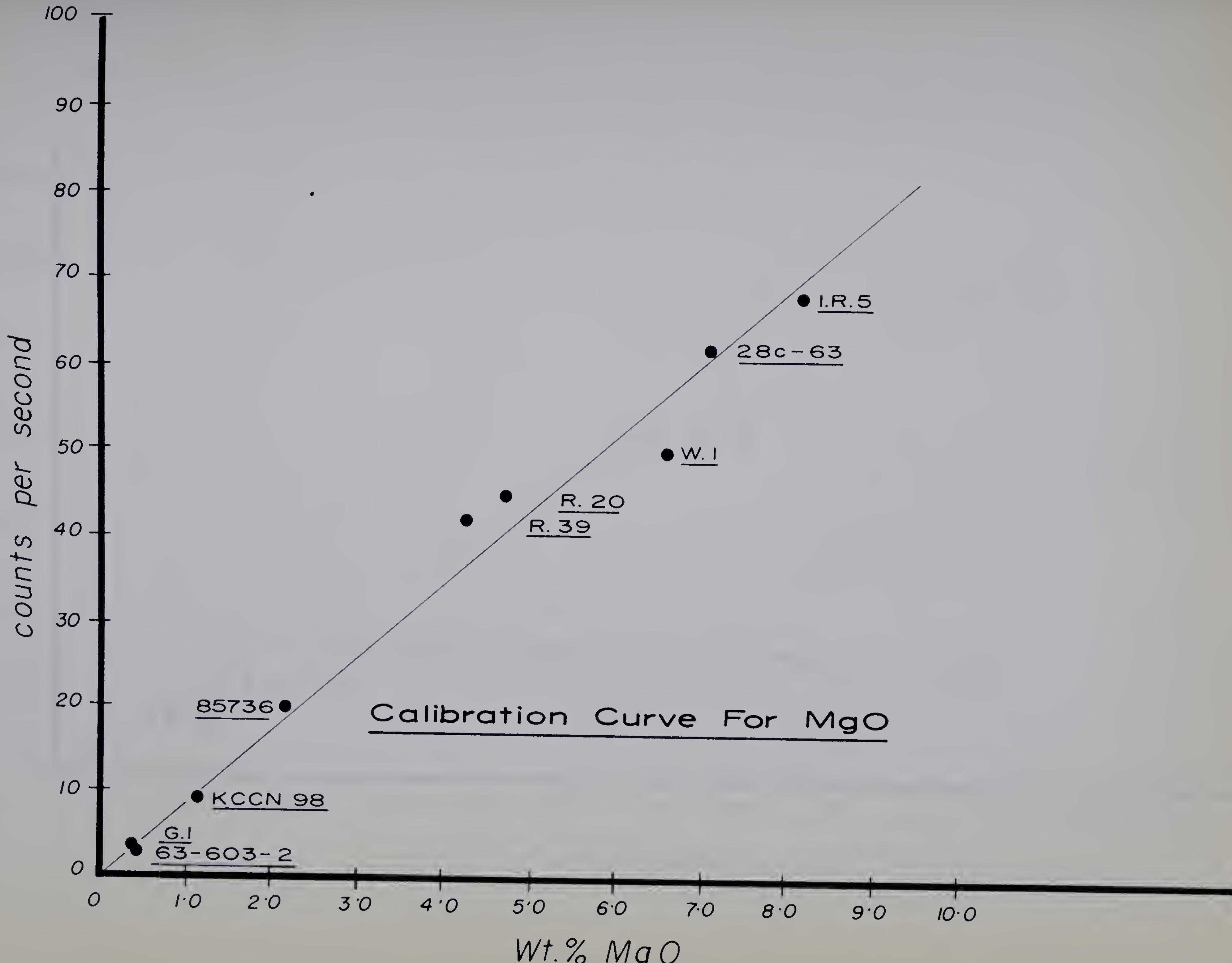
Calibration Curve For MgO
counts per second
Wt.% MgO
100
90
80
70
60
50
40
30
20
10
0
1·0
2·0
3·0
4·0
5·0
6·0
7·0
8·0
9·0
10·0
I.R.5
28c-63
W.1
R. 20
R. 39
85736
KCCN 98
G.1
63-603-2

Figure 23.

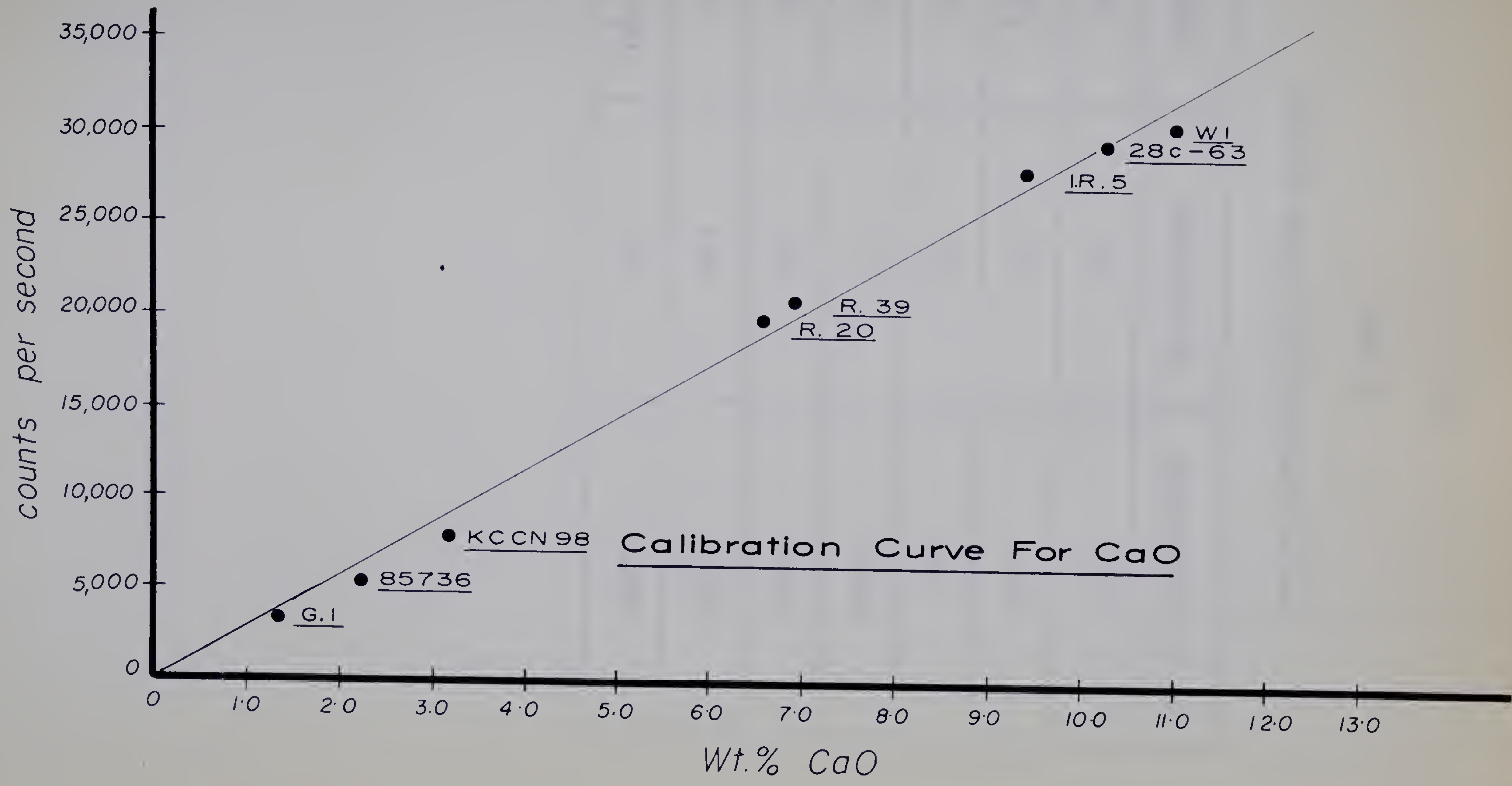
Calibration Curve For CaO
counts per second
Wt.% CaO
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
1·0
2·0
3.0
4·0
5.0
6·0
7·0
8·0
9·0
10·0
11·0
12·0
13·0
G.1
85736
KCCN98
R. 20
R. 39
I.R.5
28c-63
W1

Figure 24.

Table 22

Statistical data for X-ray fluorescence analyses

OXIDE	PRECISION (%)	DETECTABILITY (wt. %)
MgO	1.85	0.15
Al_2O_3	0.15	0.056
SiO_2	1.39	0.22
CaO	0.14	0.0095
TiO_2	0.44	0.0011
MnO	0.42	0.0017
Total Fe_2O_3	0.13	0.0093

APPENDIX B

FERROUS OXIDE DETERMINATION

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FERROUS OXIDE DETERMINATION

RESUME OF PROCEDURE

The method adopted for ferrous oxide determination for both garnets and their host rocks was essentially that of Groves's modification of the Rowledge method (Groves, 1951, p. 184).

0.2 gm. of finely ground specimen was used in each determination. The sodium metafluoborate flux was prepared in the manner advocated by Rowledge and 1.2 gm. used per determination. Fusion was carried out in a silica boat, in an inert atmosphere of nitrogen (the nitrogen had been bubbled through pyrogallol to remove any oxygen). A silica combustion tube was used and the heat for fusion was supplied by means of a Meker burner and an oxygen-gas torch.

The silica tube was thoroughly purged with nitrogen prior to each fusion. An adequate time for fusion was found to be 15 to 20 minutes. The current of nitrogen was continued following fusion, until the tube was cool. The boat and its contents were transferred to a conical flask containing 100 cc of air-free boric acid solution and 7 cc of concentrated sulphuric acid. Nitrogen was bubbled through the flask until the contents was brought to a boil. After solution was completed (approximately two hours), the flask and contents were cooled to room temperature under the tap and titrated to the first pinkish colour with standard potassium permanganate solution.

NOTEWORTHY POINTS CONCERNING THE PROCEDURE

1. Specimens should be ground as finely as possible for both ease and completeness of fusion.

2. The use of the platinum boat, although providing rapidity and ease of fusion, proved unsuccessful due to the heavy staining by FeO (loss of FeO is probably greater than 0.5%). Leaching of the platinum boat with concentrated hydrochloric acid for the recovery of FeO, is both arduous and time consuming. As a consequence, a silica boat was used in preference to the platinum.

3. The silica boat, although more difficult to heat for complete fusion, consistently gave rise to higher FeO values than the platinum. Dissolving the fused mass, however, takes a longer time (up to two hours are necessary). If this latter process is carried out for shorter periods than one hour, low values are apt to be obtained.

4. An adequate period for purging with nitrogen of the silica combustion tube containing the boat together with sample, is essential prior to the fusion process in order to expel any traces of air.

5. A 15 to 20 minute period for fusion proves adequate. The Meker burner alone is insufficient to make the flux completely molten; added heat from an oxygen-gas torch is necessary.

6. Air-free boric acid solution is obtained by boiling the solution for approximately 30 minutes and nitrogen is bubbled through the solution while it cools. This process can be carried out while the tube and fused sample are

cooling by using an extention line from the combustion tube.

7. If a saturated solution of boric acid is used, evaporation during the lengthy process of dissolving the fused sample will cause supersaturation of the boric acid solution, resulting in the precipitation of boric acid upon cooling of the solution. The presence of boric acid crystals at the time of titration makes the end-point difficult to discern. An undersaturated solution of boric acid provides the desired results.

8. The Rowledge method proves to be highly unsatisfactory where there is high water content in samples. A trial run with Mohr's salt (ie. hydrated ferrous ammonium sulphate), demonstrated this convincingly.

APPENDIX C

OPERATING CONDITIONS FOR X-RAY POWDER PHOTOGRAPHY, AND STATISTICAL METHODS ADOPTED TO DETERMINE UNIT CELL PARAMETER VALUES AND ERRORS

APPENDIX C

OPERATING CONDITIONS FOR X-RAY POWDER PHOTOGRAPHY

The powder photographs of twenty-five garnets were taken with a large (114.6 mm.) standard Philips Debye-Scherrer camera, on a Norelco power unit. The source of radiation was a cobalt tube energized by 25 KV and 15 MA; the emitted radiation was screened through an iron filter. An adequate time for each exposure was two hours.

STATISTICAL METHODS ADOPTED TO DETERMINE CELL PARAMETER VALUES AND ERRORS

(1) For the best fit straight line in the Nelson-Riley Extrapolation Plot:

Using a method of least squares, the best fit straight line was determined for each extrapolation plot. The value of the intercept on y of each determined regression line was taken as the accurate value for the unit cell parameter.

The slope b of each straight line,

$$y = a + bx \qquad \text{(where } a \text{ equals the intercept on } y\text{)},$$

was determined by means of the following equation;

$$b = \frac{n\,\Sigma x_i y_i - (\Sigma x_i)(\Sigma y_i)}{n\,\Sigma x_i^2 - (\Sigma x_i)^2}$$

where n = no. of observations

$$x_i = f(\theta); \quad \text{ie. } \frac{1}{2}\left[\left(\frac{\cos^2\theta}{\sin\theta} + \frac{\cos^2\theta}{\theta}\right)\right]$$

$$y_i = a_{app}$$

The intercept a, and hence the accurate unit cell parameter, was obtained by means of the following equation;

$$a = \frac{1}{n}\Sigma y_i - b\frac{1}{n}\Sigma x_i$$

(2) Error determination in unit cell parameter measurement made from the regression line:

The residual error (Σd_i^2), was calculated as follows: each value of x_i and y_i were substituted in the straight line equation,

$$y = a + bx$$

and $(y_i - a - bx_i)$ was found for each set of readings, squared, and a summation made (ie. $= (\Sigma d_i^2)$.

$$\text{then } \alpha^2 = \frac{\Sigma d_i^2}{(n - 2)}$$

The standard error in cell parameter measurement, α_a, was then obtained from the following equation:

$$\frac{\alpha_a^2}{\Sigma x_i^2} = \frac{\alpha^2}{n\Sigma x_i - (\Sigma x_i)^2}$$

N.B. (The value of a_o, the unit cell parameter, will fall within the limits covered by α_a, in 68 times out of one hundred, if the above procedure is adopted.)